Status report on η' experiments

PRiME

II. Physikalisches Institut

Dr. Stefan Friedrich

for the η-PRiME collaboration

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

NUSTAR Annual Meeting 2015
GSI, March 4th, 2015

Content

- **Introduction: Theoretical predictions for the meson-nucleus optical potential**
- **Experimental approaches and results on the optical potential**
- **Search for meson-nucleus bound states**
- **Summary and Outlook**

Status report on η' experiments

The η-PRiME collaboration

Y. Ayyad, J. Benlliure, K.-T. Brinkmann, S. Friedrich, H. Fujioka, H. Geissel, J. Gellanki, C. Guo, E. Gutz, E. Haettner, M. N. Harakeh, R. S. Hayano, Y. Higashi, S. Hirenzaki, C. Hornung, Y. Igarashi, N. Ikeno, K. Itahashi, M. Iwasaki, D. Jido, N. Kalantar-Nayestanaki, R. Kanungo, R. Knoebel, N. Kurz, V. Metag, I. Mukha, T. Nagae, H. Nagahiro, M. Nanova, T. Nishi, H. J. Ong, S. Pietri, A. Prochazka, C. Rappold, M. P. Reiter, J. L. Rodriguez-Sánchez, C. Scheidenberger, H. Simon, B. Sitar, P. Strmen, B. Sun, K. Suzuki, I. Szarka, M. Takechi, Y. K. Tanaka, I. Tanihata, S. Terashima, Y. N. Watanabe, H. Weick, E. Widmann, J. S. Winfield, X. Xu, H. Yamakami, J. Zhao

Bound states in general

Gravitation

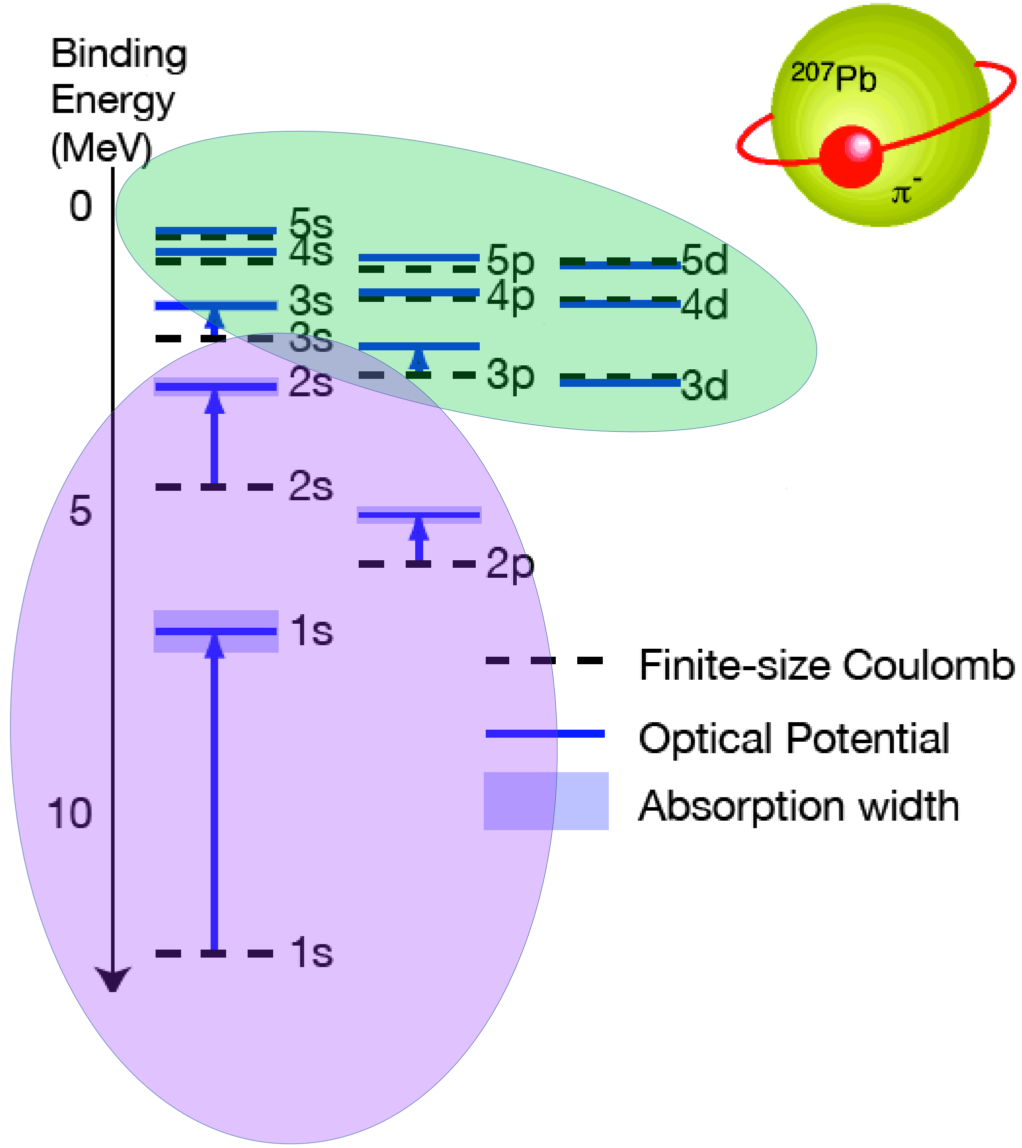
Bound system Earth $\leftrightarrow$ Moon

Bound states in general

Gravitation

Bound system
Earth ↔ Moon

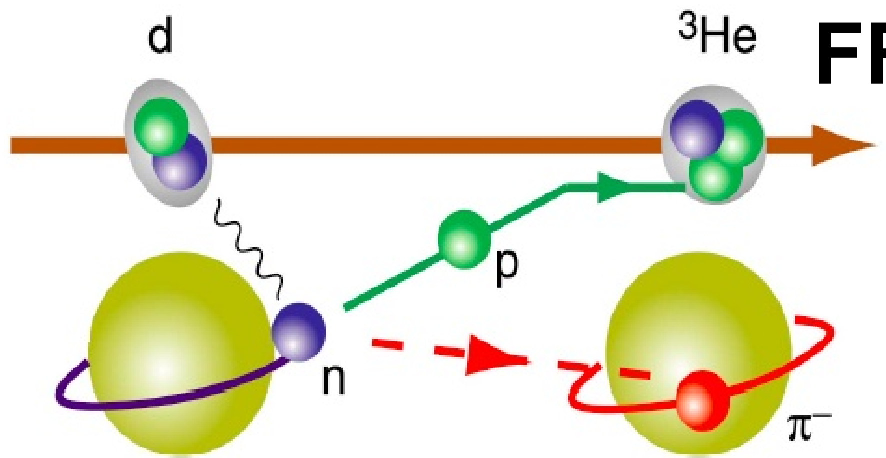
Electromagnetic (+Strong) interaction



Bound system
negatively charged pion ↔ atomic nucleus

Pion-nucleus interaction

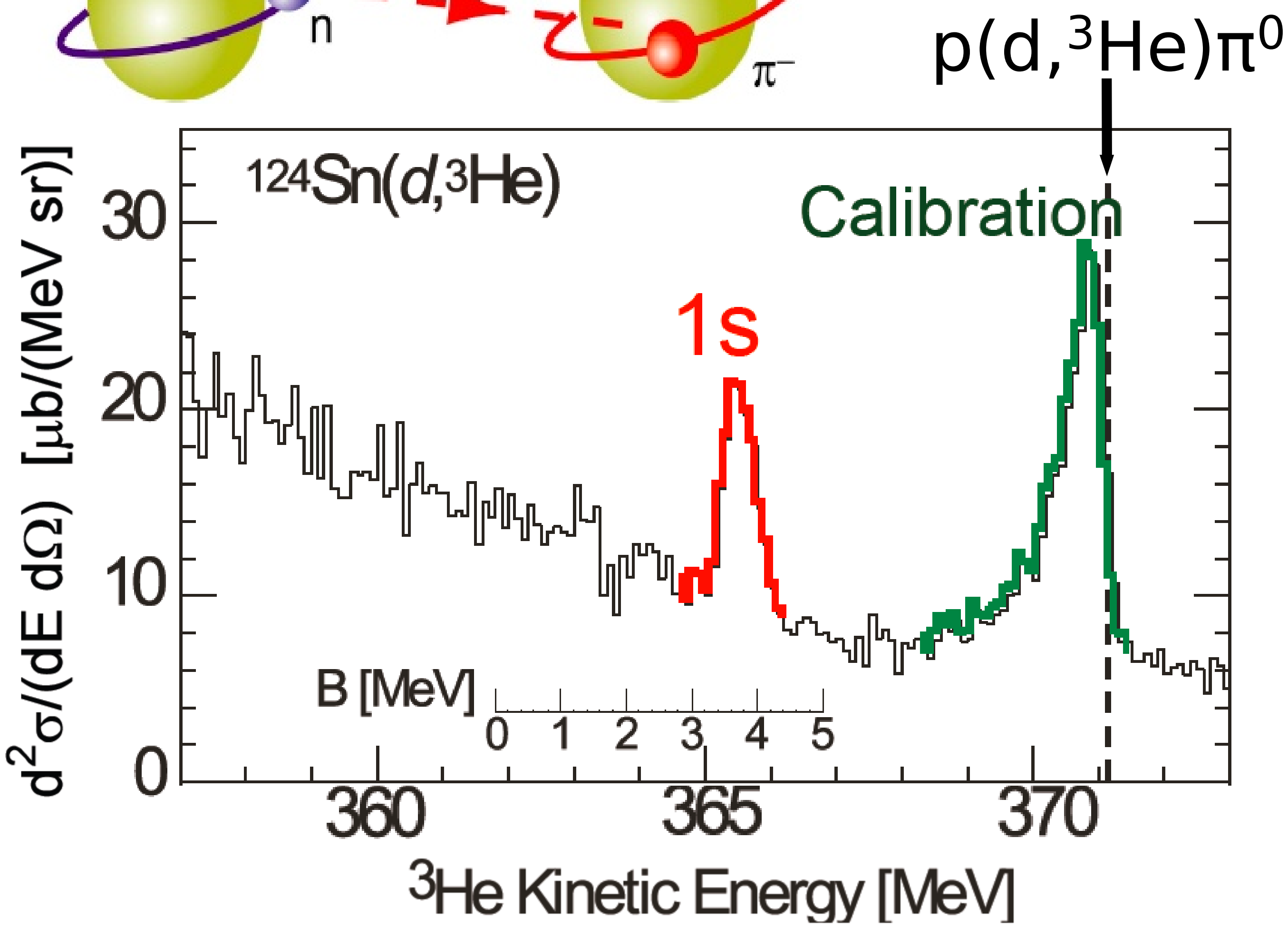
- **Deeply bound pionic (π^-) states: potential pocket due to superposition of attractive Coulomb and repulsive strong interaction**

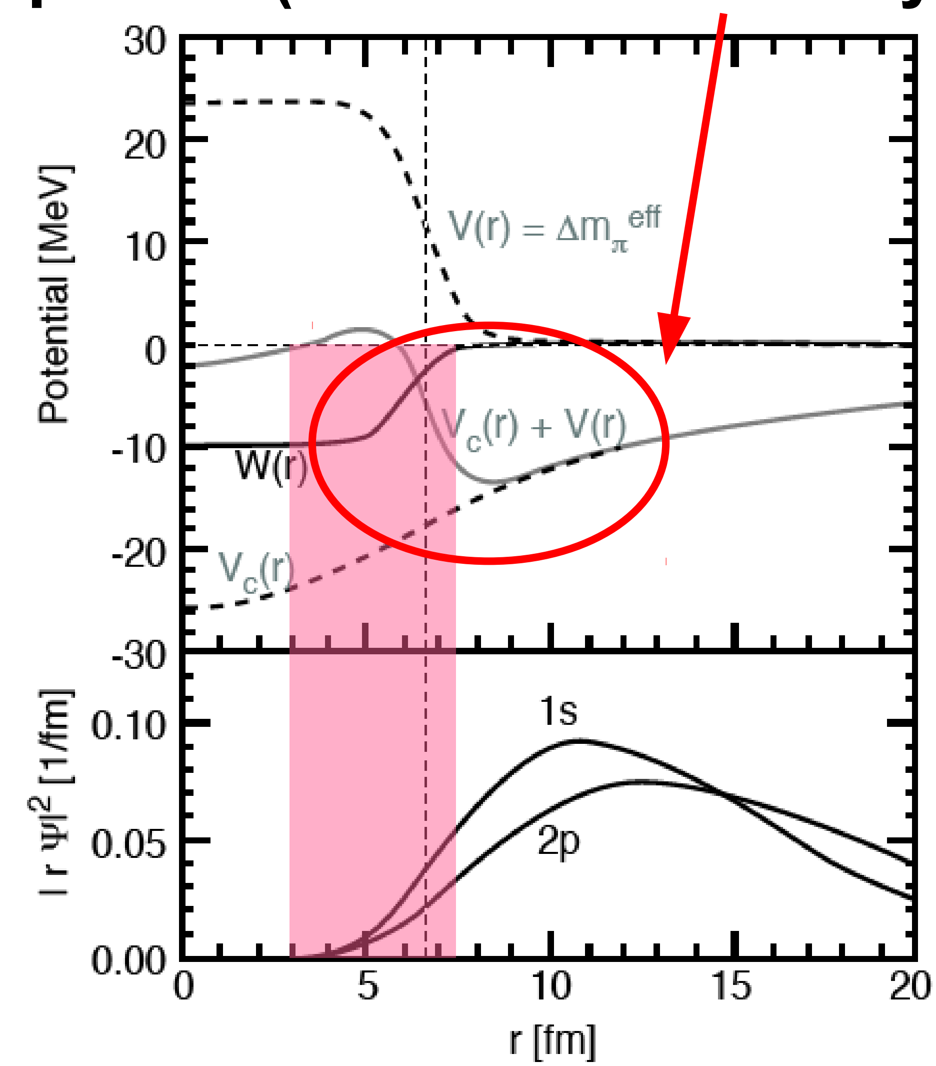


FRS@GSI

- **Pion is partly embedded in the nucleus**
- **Overlap of nuclear and Coulomb force**

→ potential pocket (halo-like nuclear system)





- Gilg et al., PRC 62 (2000) 025201
- Itahashi et al., PRC 62 (2000) 025202
- Geissel et al., PRL 88 (2002) 122301
- Suzuki et al., PRL 92 (2004) 072302

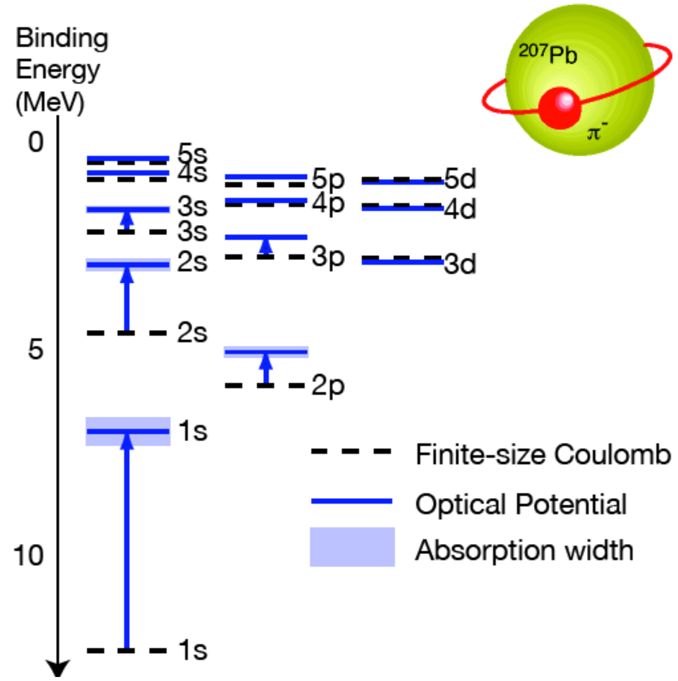
- Toki, Hirenzaki, Yamazaki, Hayano, NPA 501 (1989) 653
- Kienle, Yamazaki, PPNP 52 (2004) 85
- Yamazaki, Hirenzaki, Hayano, Toki, Phys. Rep. 514 (2012) 1

Bound states in general

Gravitation

Earth ↔ Moon

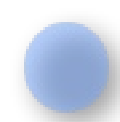
EM (+Strong) interaction



charged pion ↔ nucleus

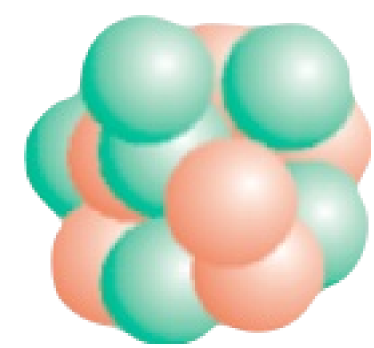
Strong interaction only

neutral meson
ω, η'



⇔

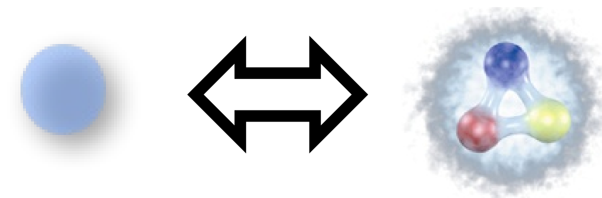
nucleus



→ mesons in nuclear medium

Meson-nucleon/nucleus interaction

I. meson-nucleon interaction:

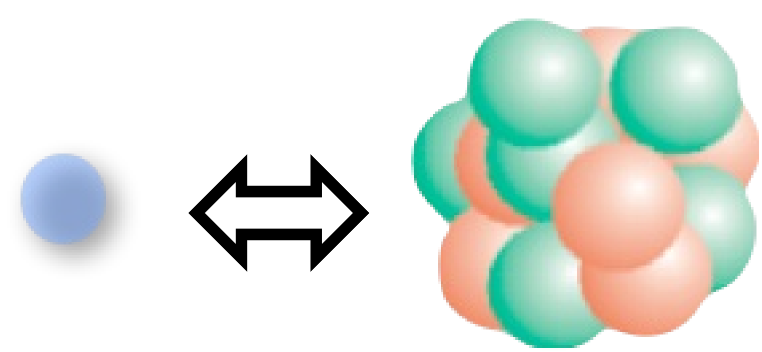
meson  nucleon

- for short-lived mesons (η, ω, η', Φ) no beams available
- study of meson-nucleon interaction by final state interactions in elementary reactions, e.g. $p + p \Rightarrow p + p + \eta'$

$\Rightarrow$ scattering length $|a|$ (only modulus)

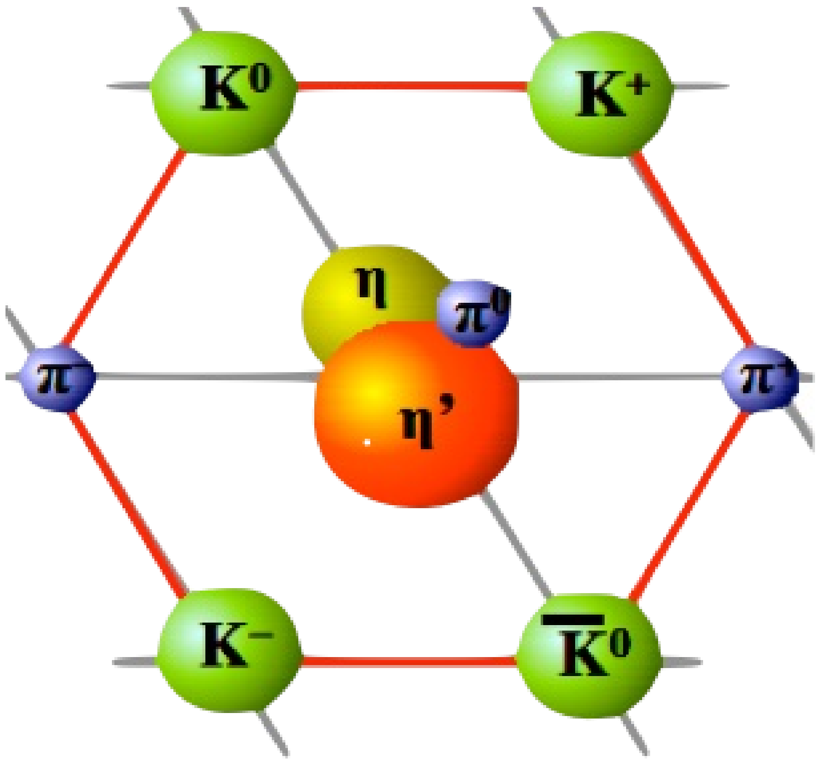
- interaction attractive or repulsive ?

II. meson-nucleus interaction:

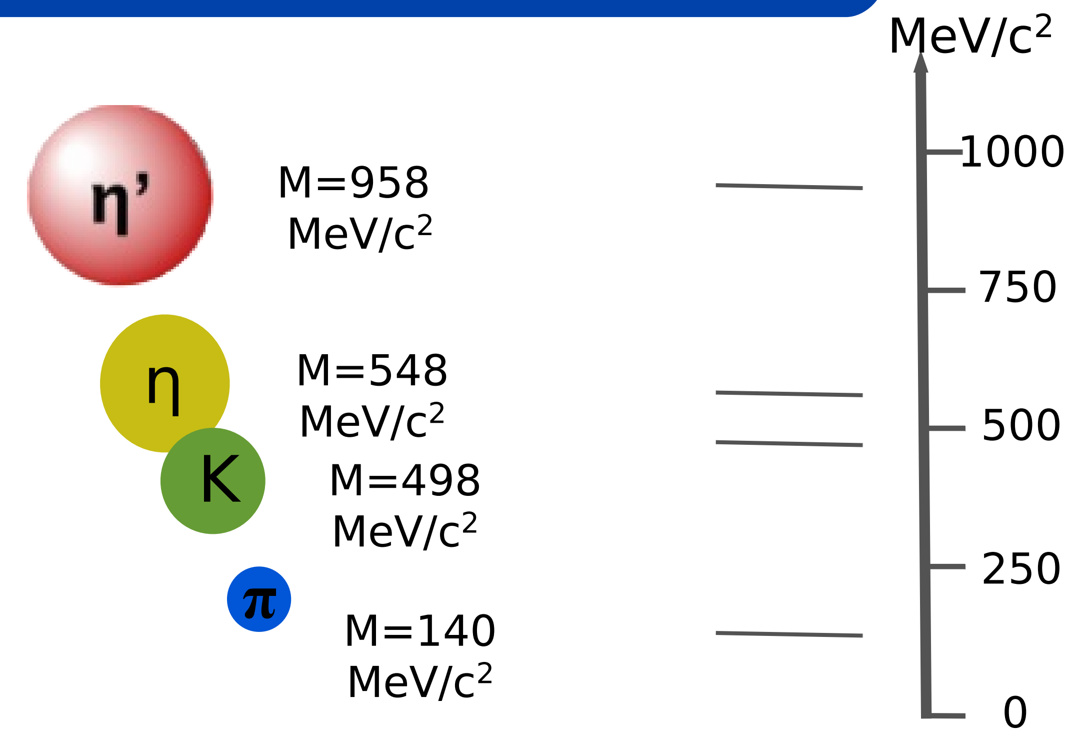
meson  nucleus

- if attractive, interaction strong enough to form meson-nucleus bound states ?

Symmetry breaking in the hadronic sector

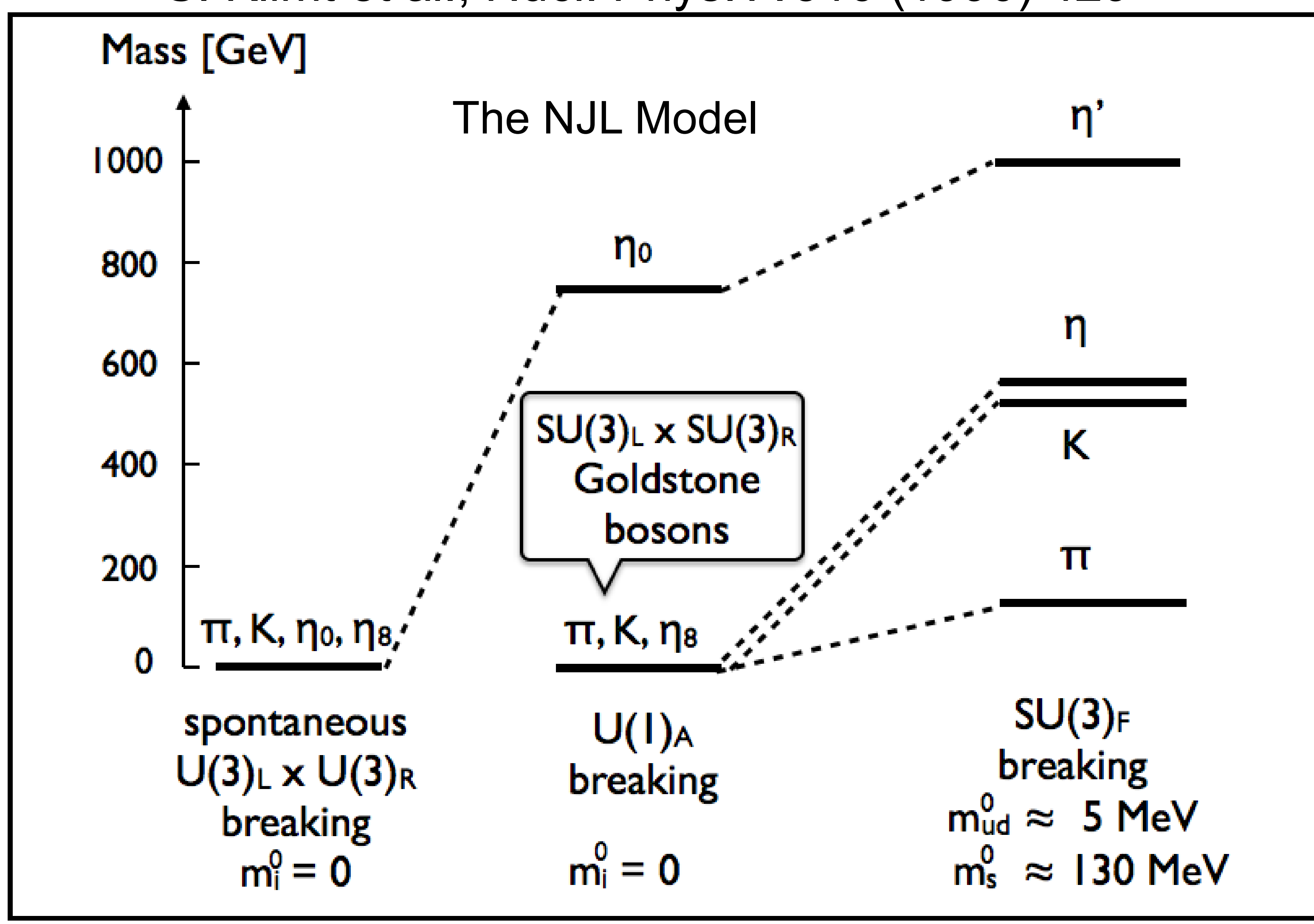


nonet of pseudoscalar mesons

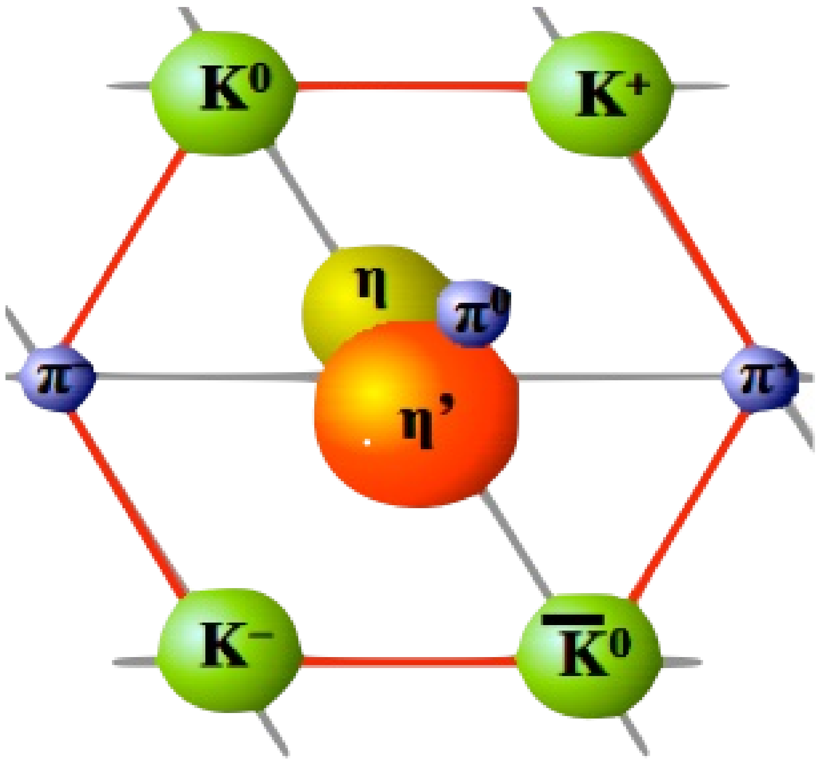


- mass as a result of symmetry breaking

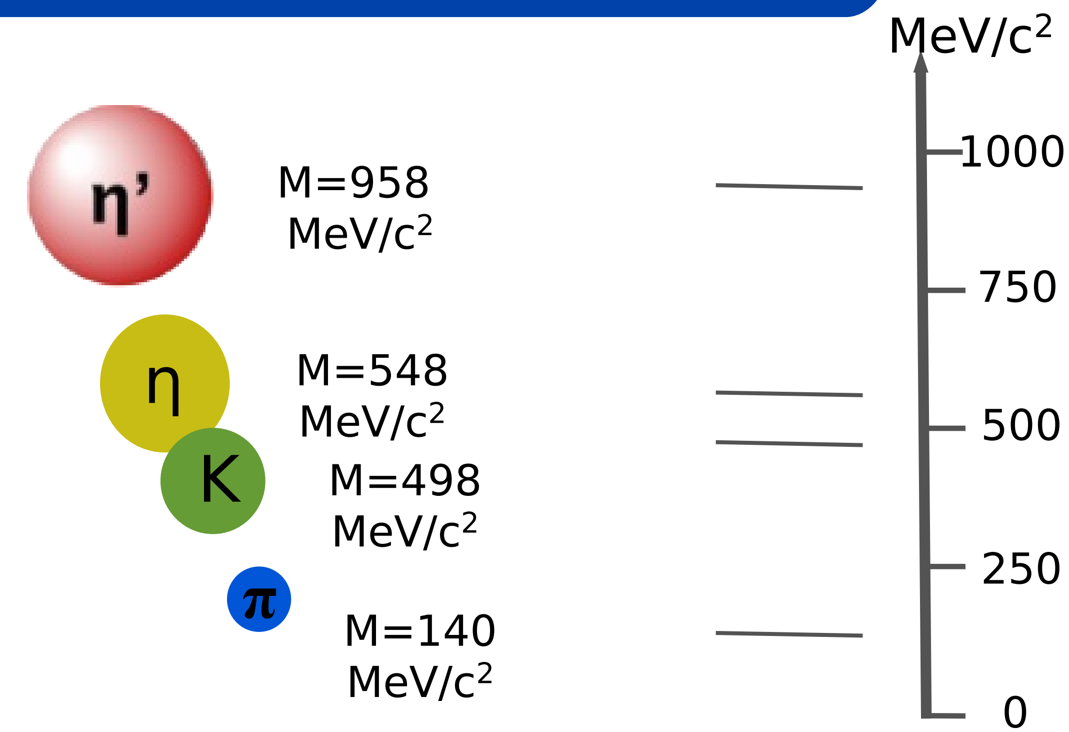
S. Klimt et al., Nucl. Phys. A 516 (1990) 429



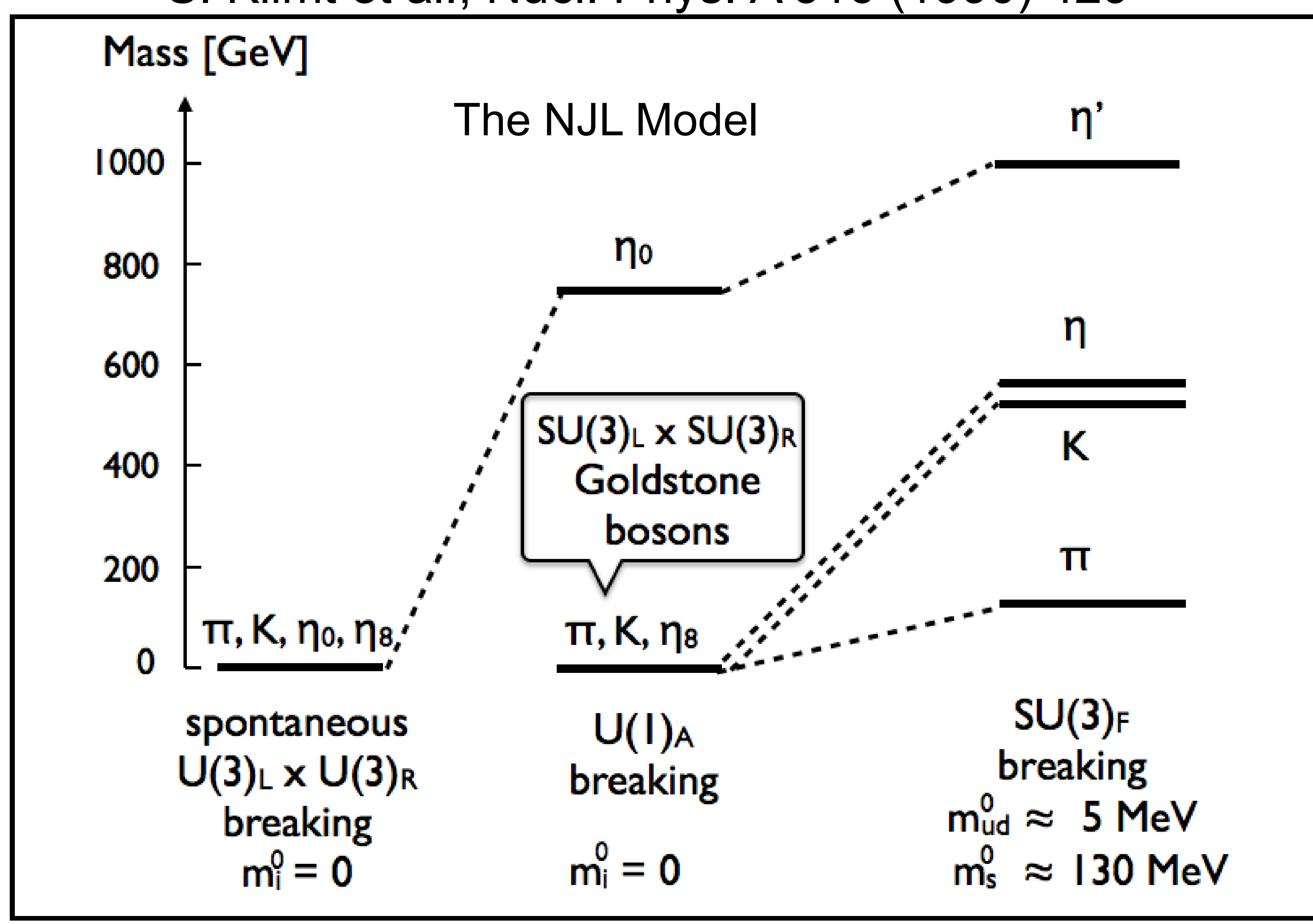
Symmetry breaking in the hadronic sector



nonet of pseudoscalar mesons



S. Klimt et al., Nucl. Phys. A 516 (1990) 429

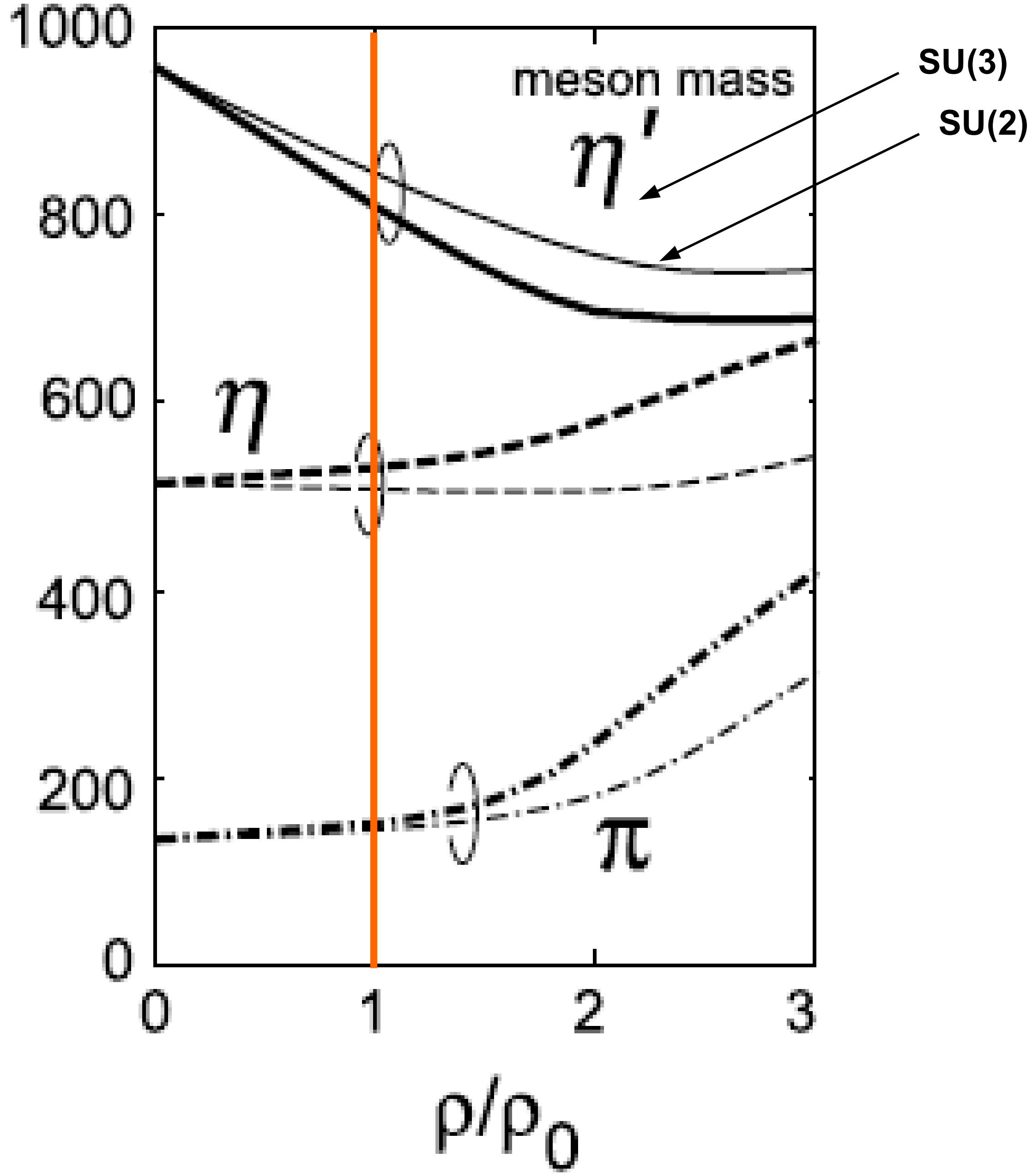


- mass as a result of symmetry breaking
- partial restoration of chiral symmetry predicted to occur in a nucleus $\Longrightarrow$ impact on meson masses?

Model predictions for the in-medium mass of the η’ meson

- NJL model

H. Nagahiro, M. Takizawa and S. Hirenzaki, Phys. Rev. C 74 (2006) 045203

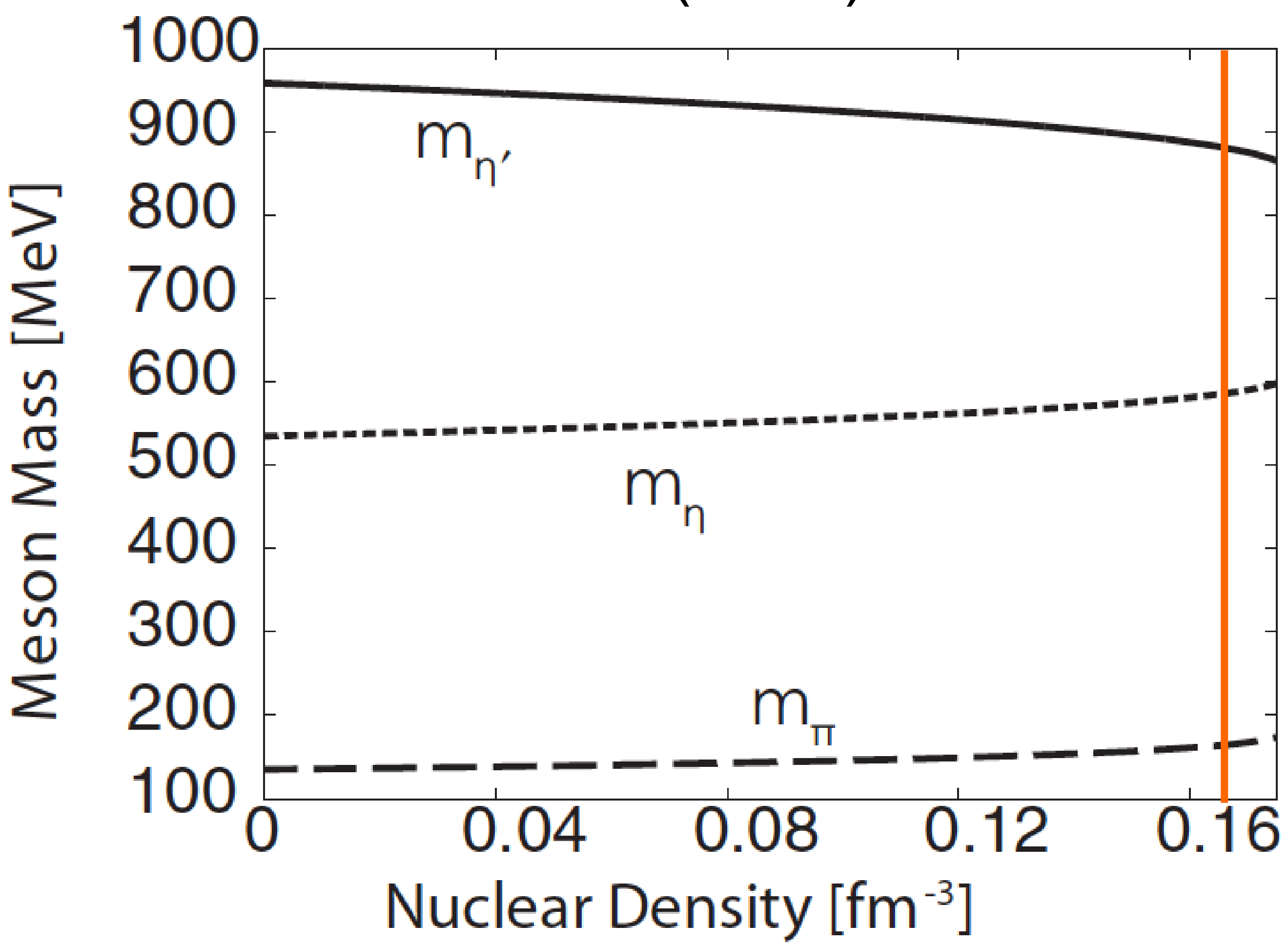


$\Delta m_{\eta'}$ (ρ_0)≈-150 MeV

Δm_{η} (ρ_0)≈+20 MeV

- linear σ-model

S. Sakai and D. Jido
PRC 88 (2013) 064906



$\Delta m_{\eta'}$ (ρ_0)≈-80 MeV

- QMC model

S. Bass and A. Thomas, PLB 634 (2006) 368

$\Delta m_{\eta'}$(ρ_0)≈-40 MeV for $\theta_{\eta\eta'}$=-20°

Experimental approaches to determine the meson-nucleus optical potential

$$U(r) = V(r) + iW(r)$$

real part

$$V(r) = \Delta m(\rho_0) \cdot \frac{\rho(r)}{\rho_0}$$

in-medium mass modification

- line shape analysis
- excitation function
- momentum distribution
- meson-nucleus bound states

imaginary part

$$W(r) = -\Gamma_0/2 \cdot \frac{\rho(r)}{\rho_0}$$
$$= -\frac{1}{2} \cdot \hbar c \cdot \rho(r) \cdot \sigma_{inel} \cdot \beta$$

lifetime shortened

in-medium width, absorption
inelastic cross section

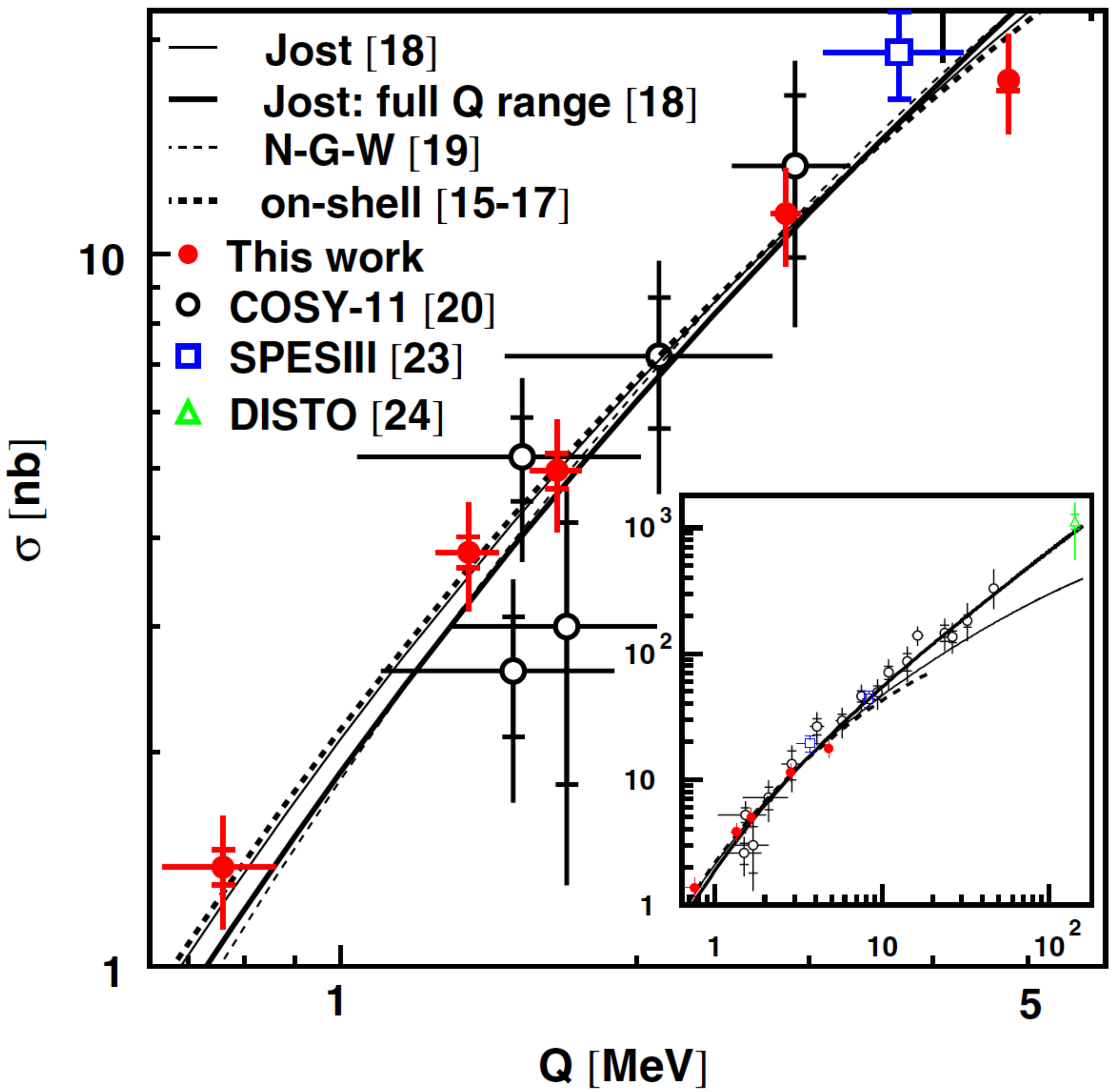
- transparency ratio measurement

$$T_A = \frac{\sigma_{\gamma A \to \eta' X}}{A \cdot \sigma_{\gamma N \to \eta' X}}$$

Mass and lifetime (width) may be changed in the medium

η′N - Scattering length @COSY-11

Extraction of scattering length from final state interactions in elementary reactions



$p + p \rightarrow p + p + \eta'$

$\mathrm{Re}(a_{\eta' p}) = (0 \pm 0.43)$ fm;
$\mathrm{Im}(a_{\eta' p}) = (0.37\,^{+0.38}_{-0.12})$ fm

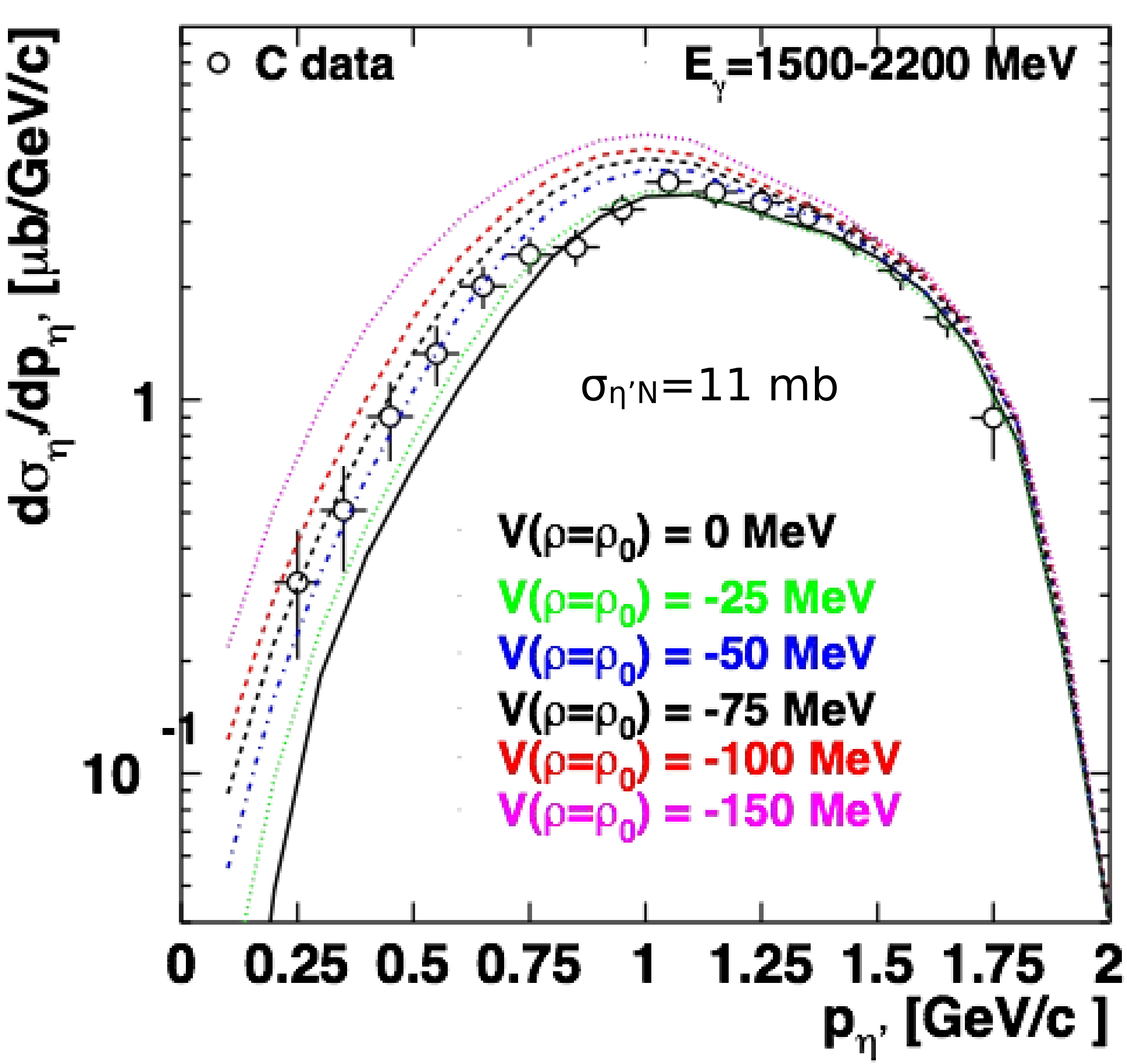
Czerwinski et al., PRL 113 (2014) 062004

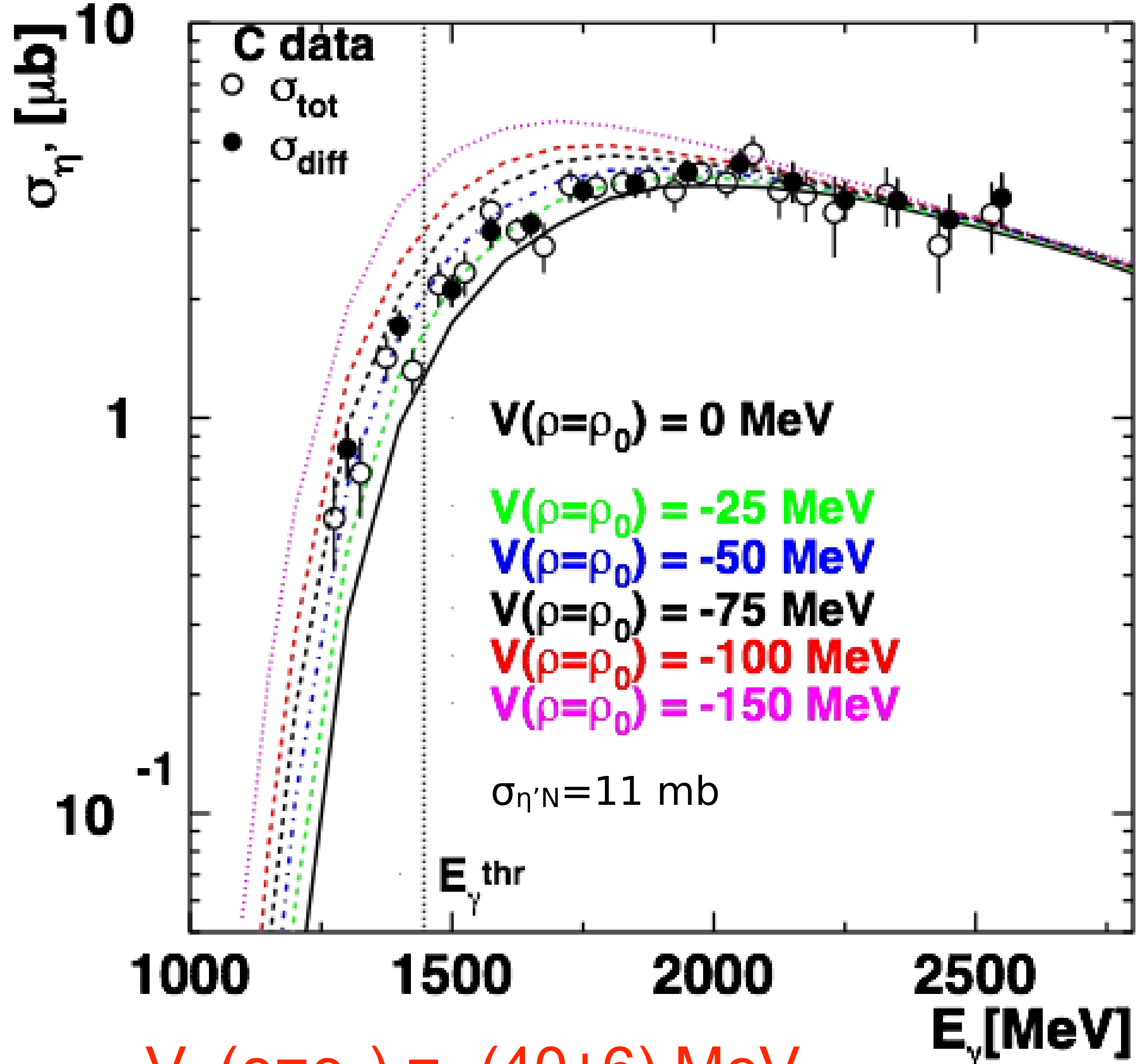
η' photoproduction off Carbon @CBELSA/TAPS

data: M. Nanova et al., PLB 727 (2013) 417
calc.: E. Paryev, J. Phys. G 40 (2013) 025201

$\gamma + {}^{12}C \rightarrow \eta' + X$
$\hookrightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$

Sensitivity on real part of potential: Weil, Mosel, Metag, PLB 723 (2013) 120





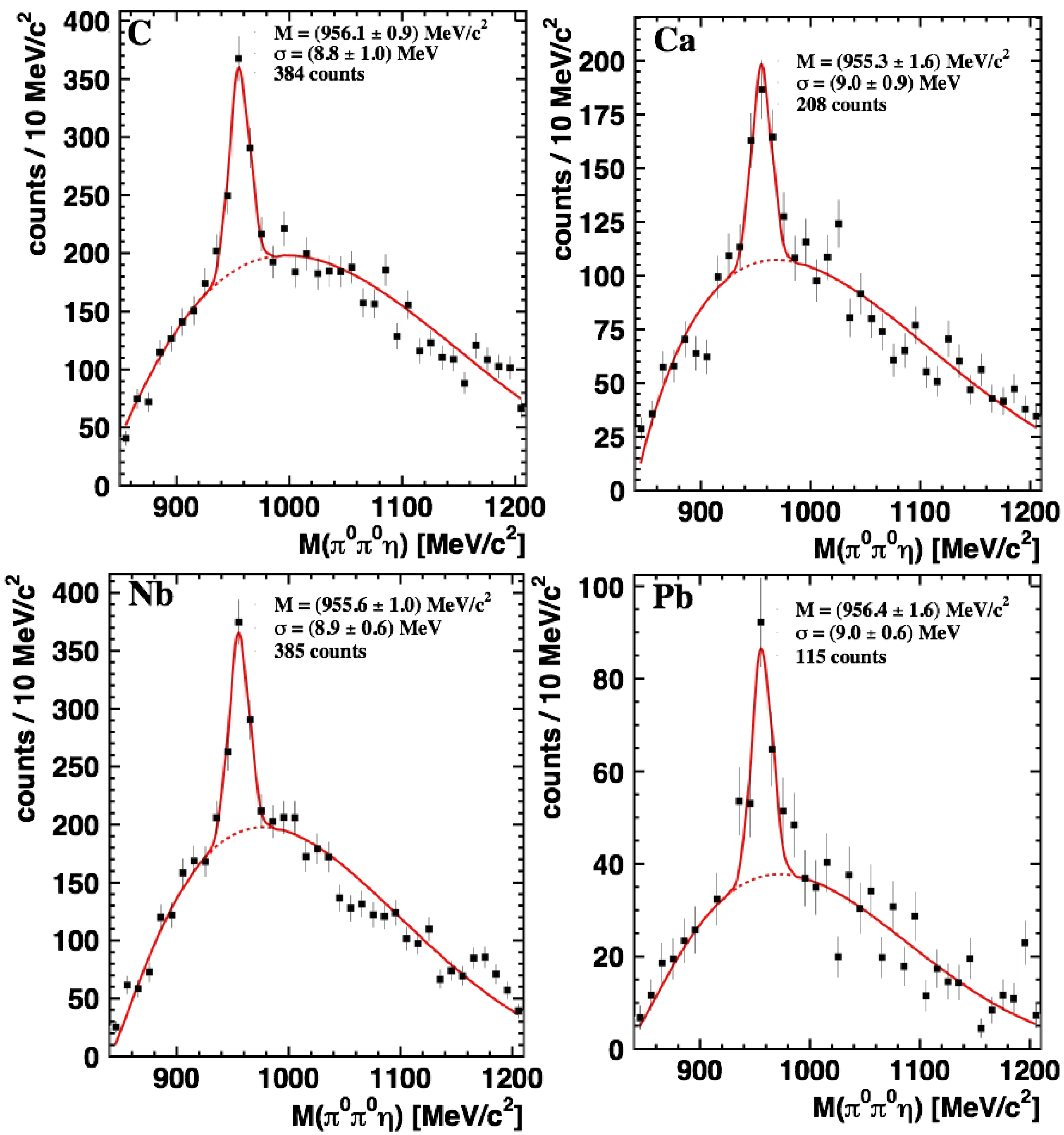
$V_{\eta'}(p_{\eta'} \approx 1.1\ \mathrm{GeV/c}; \rho=\rho_0) = -(32 \pm 11)$ MeV

$V_{\eta'}(\rho=\rho_0) = -(40 \pm 6)$ MeV
data disfavour strong mass shifts

η’ photoproduction off Carbon @CBELSA/TAPS

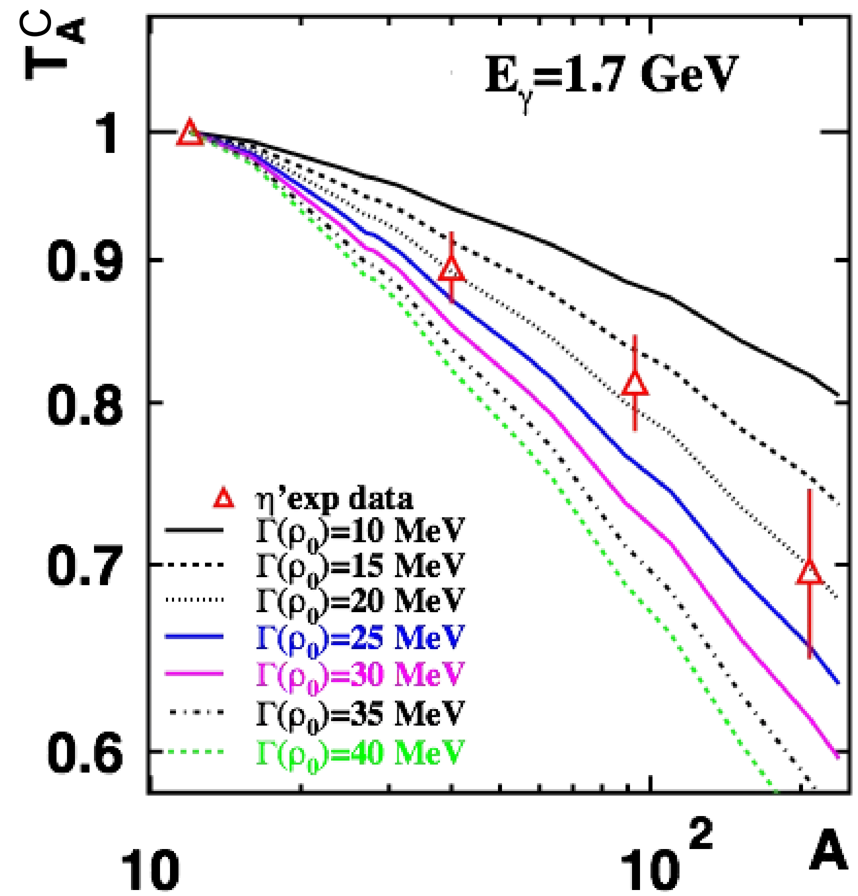
$\eta' \to \pi^0\pi^0\eta \to 6\gamma$

M. Nanova et al., PLB 710 (2012) 600



normalized to Carbon

$$T_A^C = \frac{12 \cdot \sigma_{\gamma A \to \eta' X}}{A \cdot \sigma_{\gamma C \to \eta' X}}$$



in low density approximation:

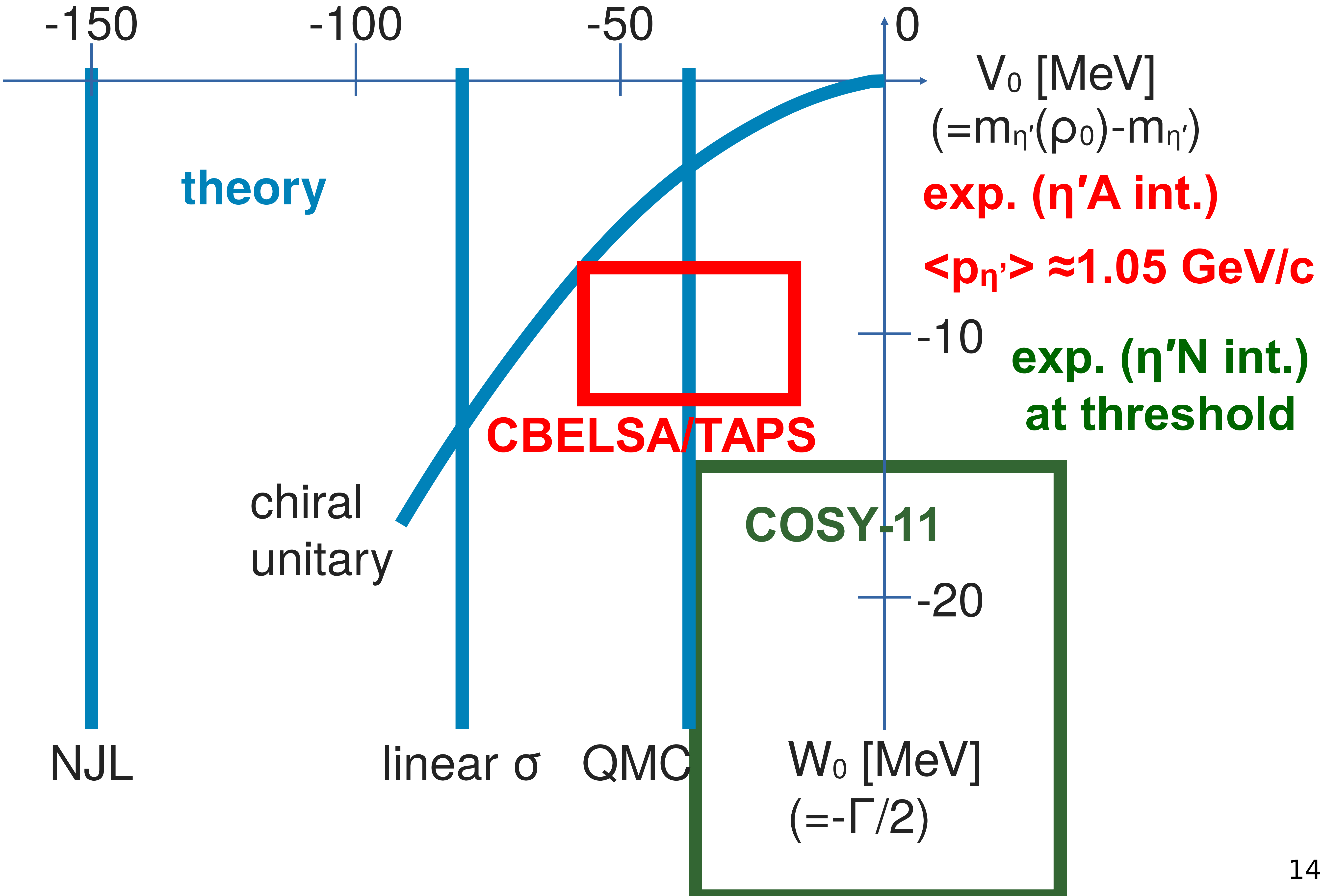
$$\Gamma(\rho) = \Gamma(\rho_0)\frac{\rho}{\rho_0} \;;\; \Gamma(\rho_0) = \hbar c \cdot \beta \cdot \rho_0 \cdot \sigma_{inel}$$

⇨ $\Gamma_{\eta'}(\langle|p_{\eta'}|\rangle \approx 1.05$ GeV/c $) \approx 15\text{-}25$ MeV

$\rho_0 = 0.17$ fm^{-3}; $\sigma^{\eta' N}_{inel} \approx 3\text{-}10$ mb

$W_{\eta'}(\rho=\rho_0) = -\Gamma_0/2 \approx -10$ MeV

η′ optical potential: state of the art

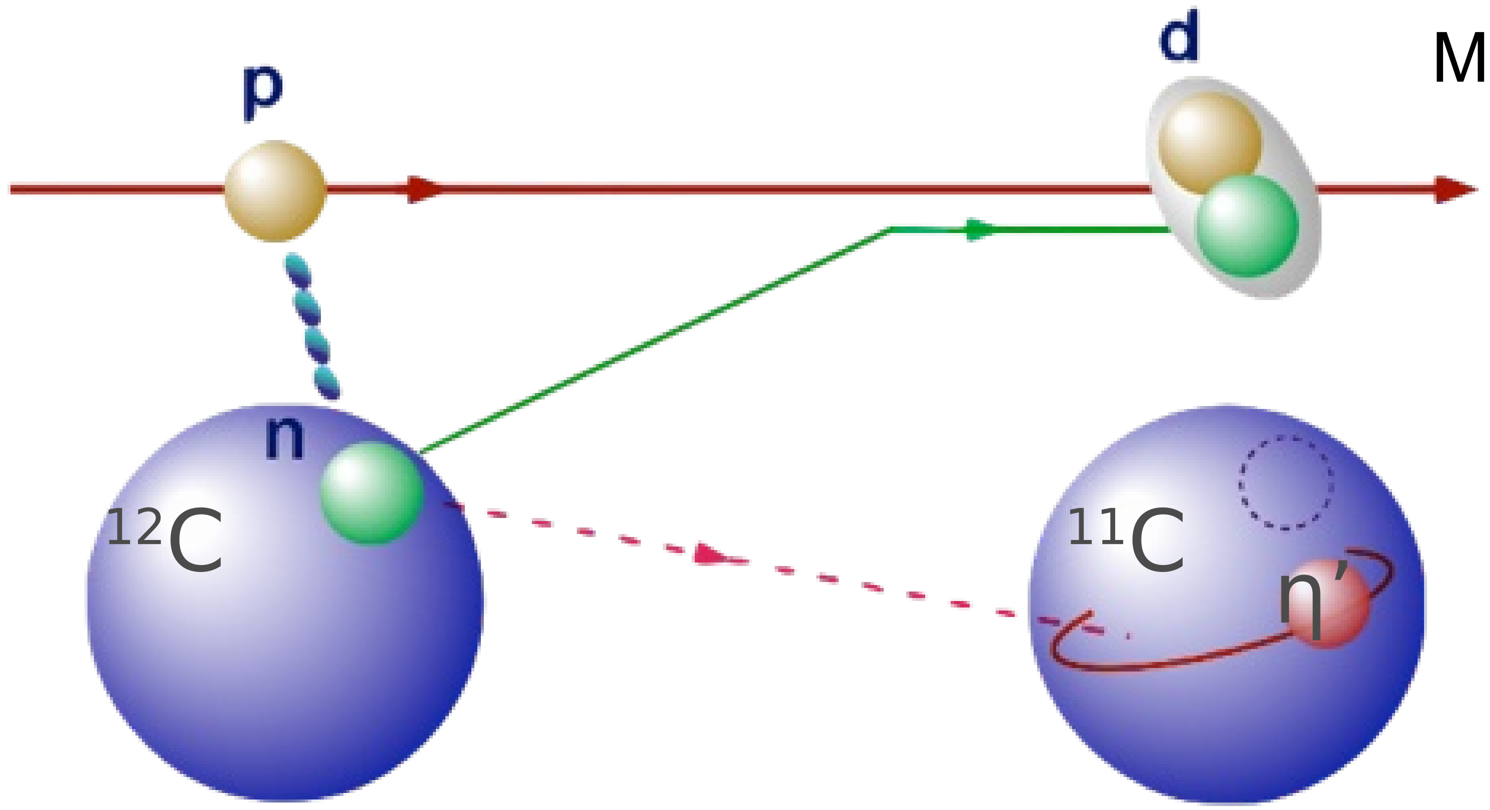


Experiment S437 (FRS@GSI): August 1-5, 2014

S437 experiment @FRS

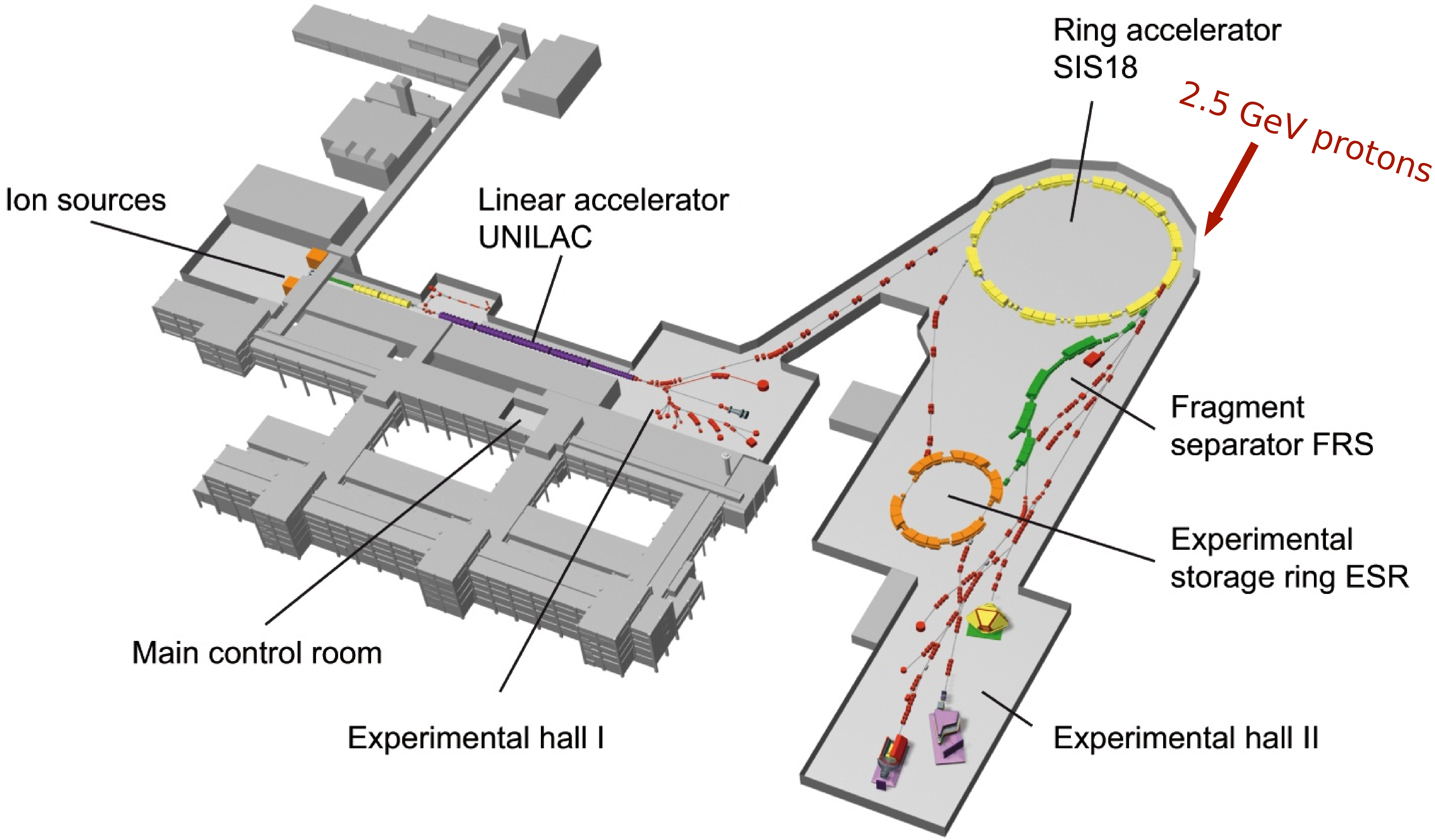
^{12}C(p,d)η'X@2.5GeV

K. Itahashi et al., Prog. Theo. Phys. 128 (2012) 601

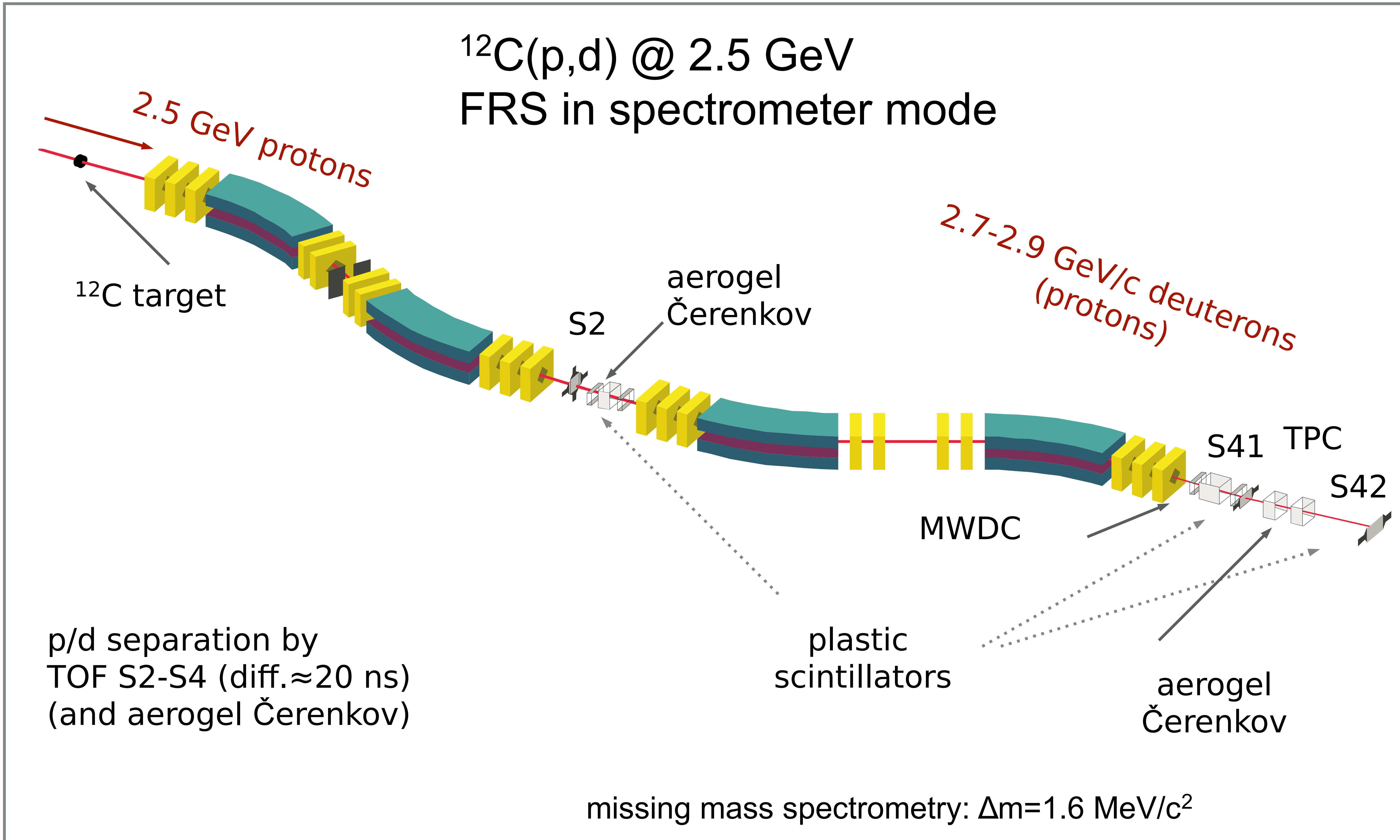


Missing mass spectroscopy

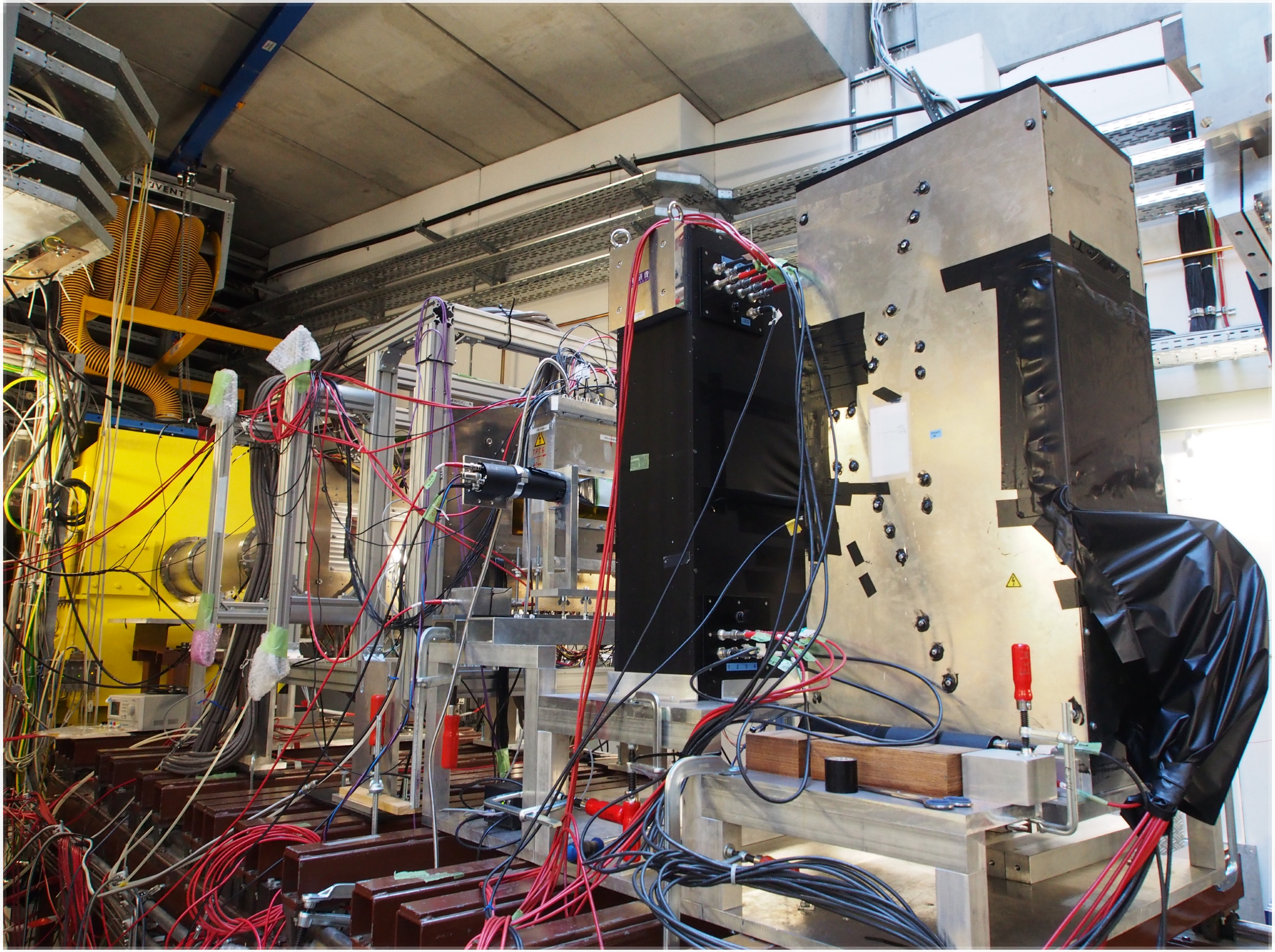
GSI accelerator complex



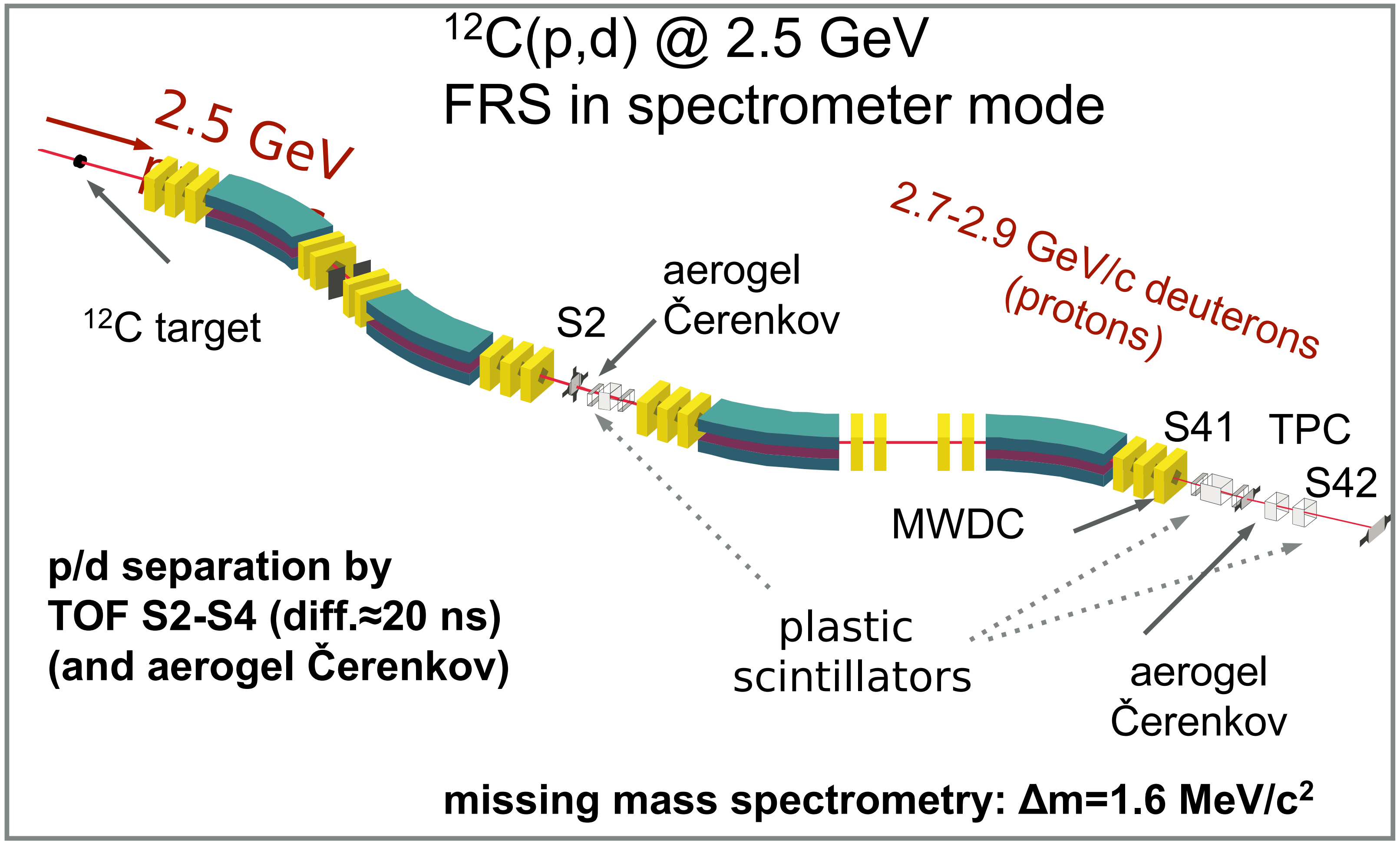
S437: experimental setup

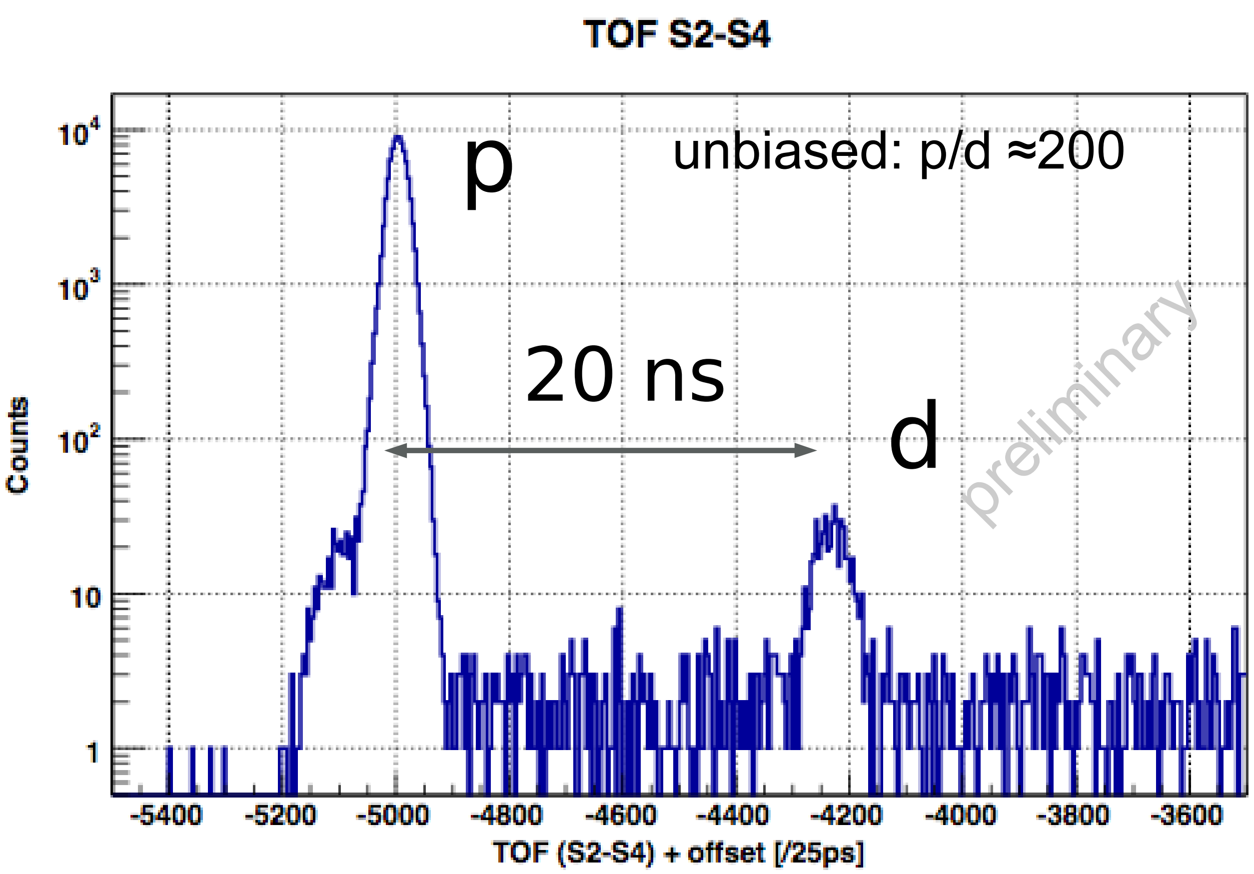


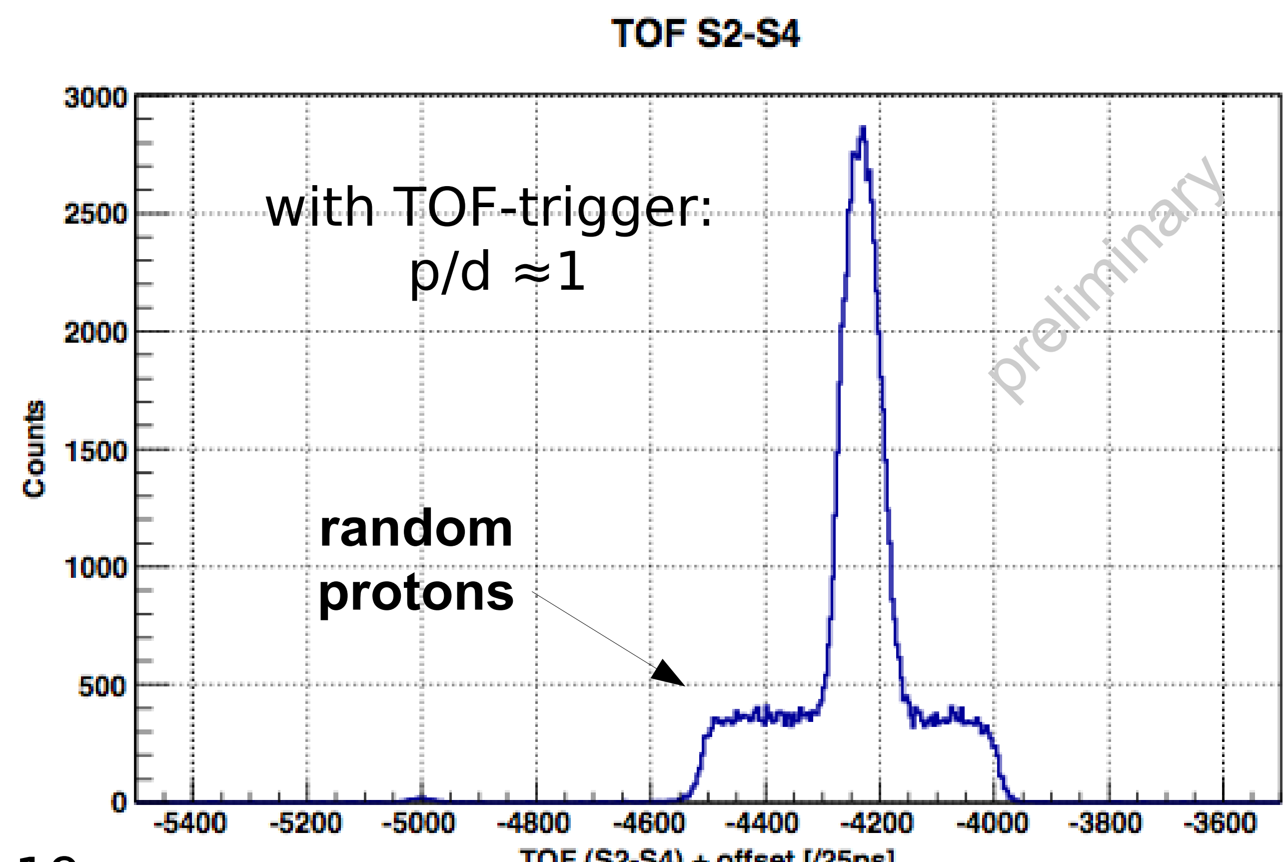
S437: experimental setup



S437: particle identification: p/d separation by TOF







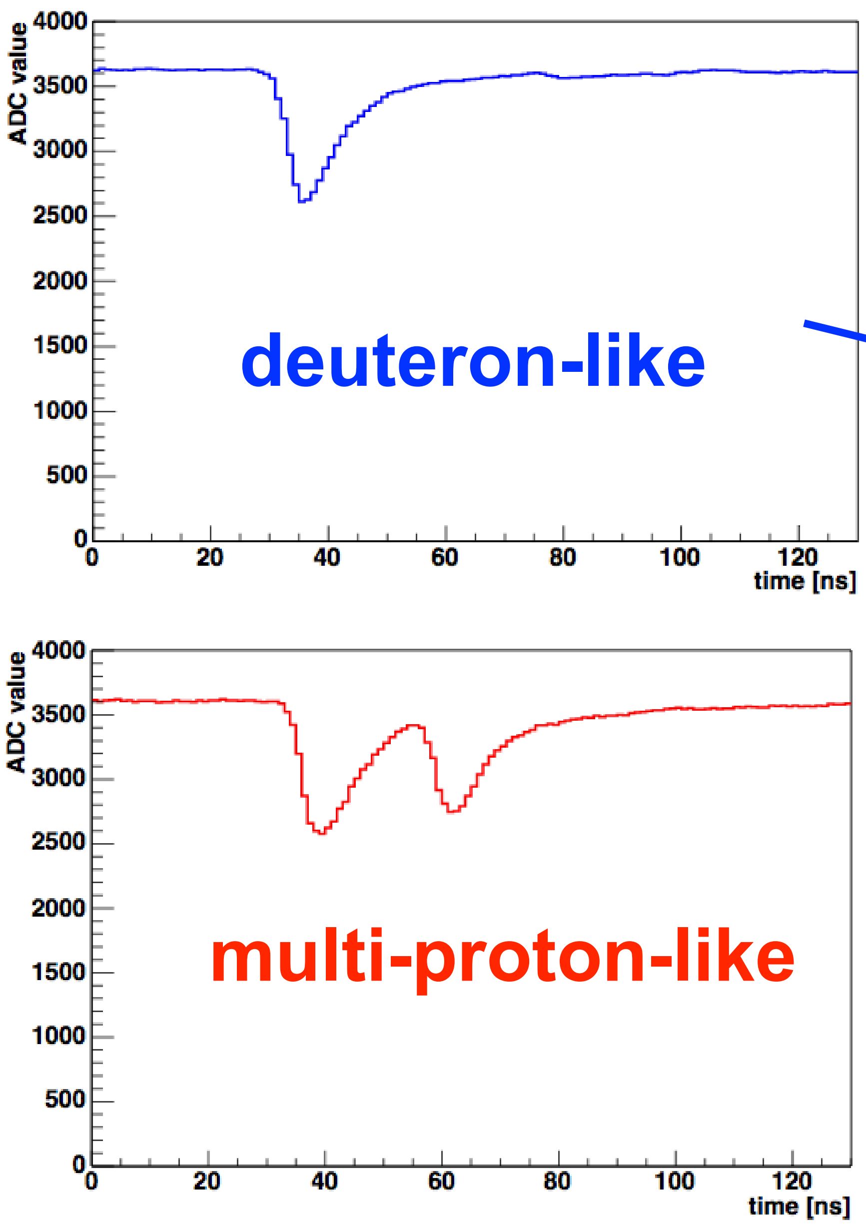
S437: particle identification

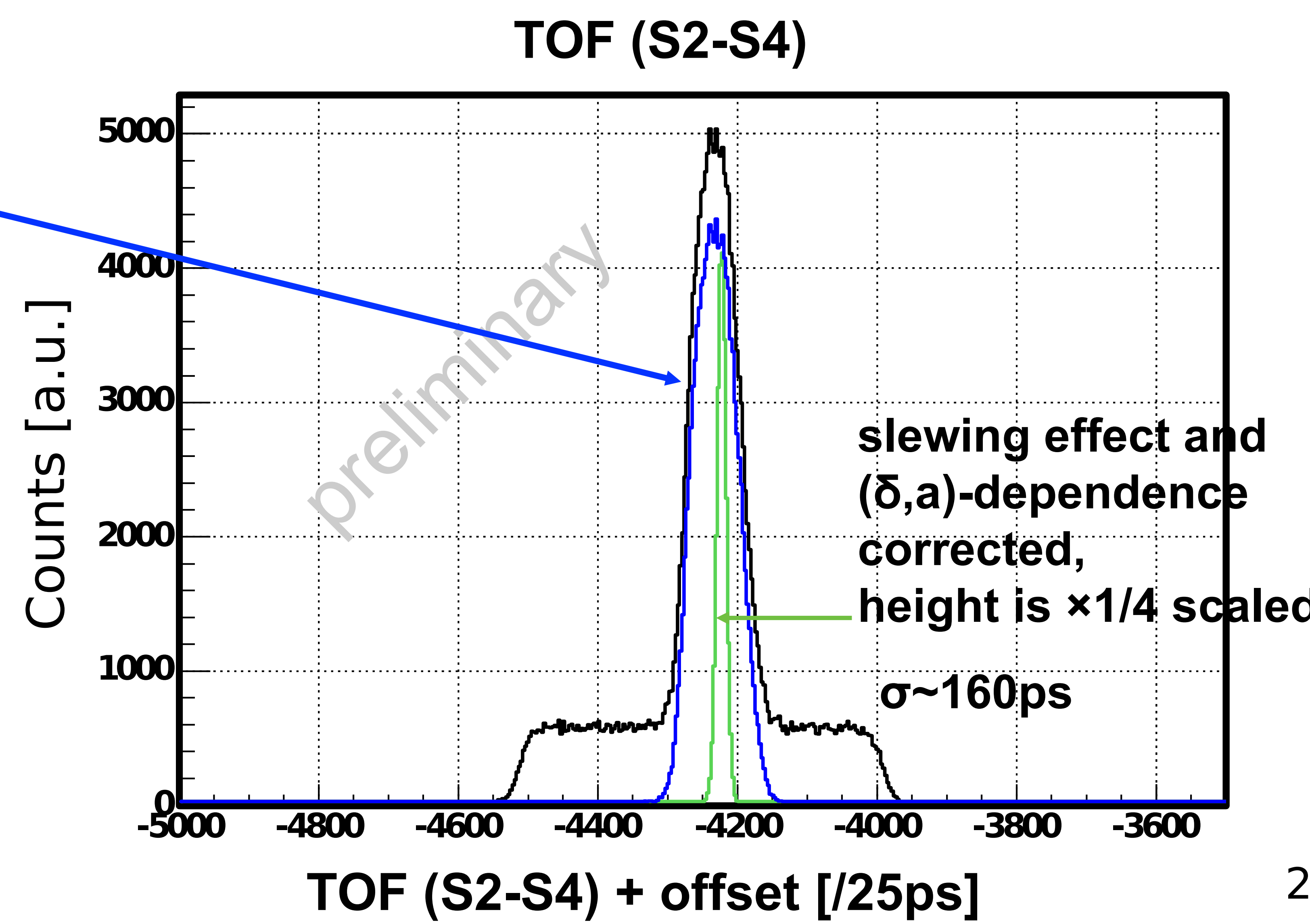
Further rejection of the accidental multi-proton in offline analysis

- **Single pulse selection by waveform analysis**
- **Cut condition for corrected TOF (S2-S4)**

→ proton contamination is sufficiently small

Examples of waveform of SC at S2

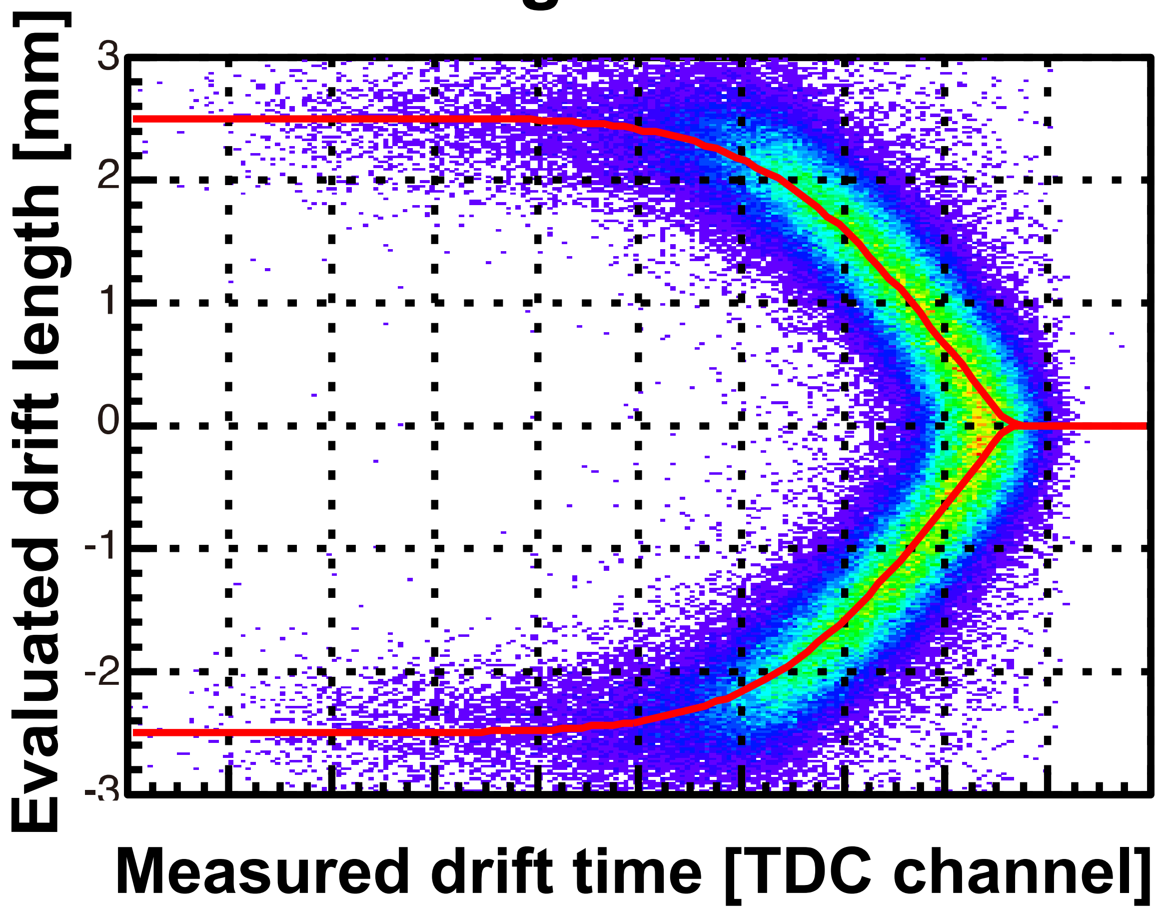




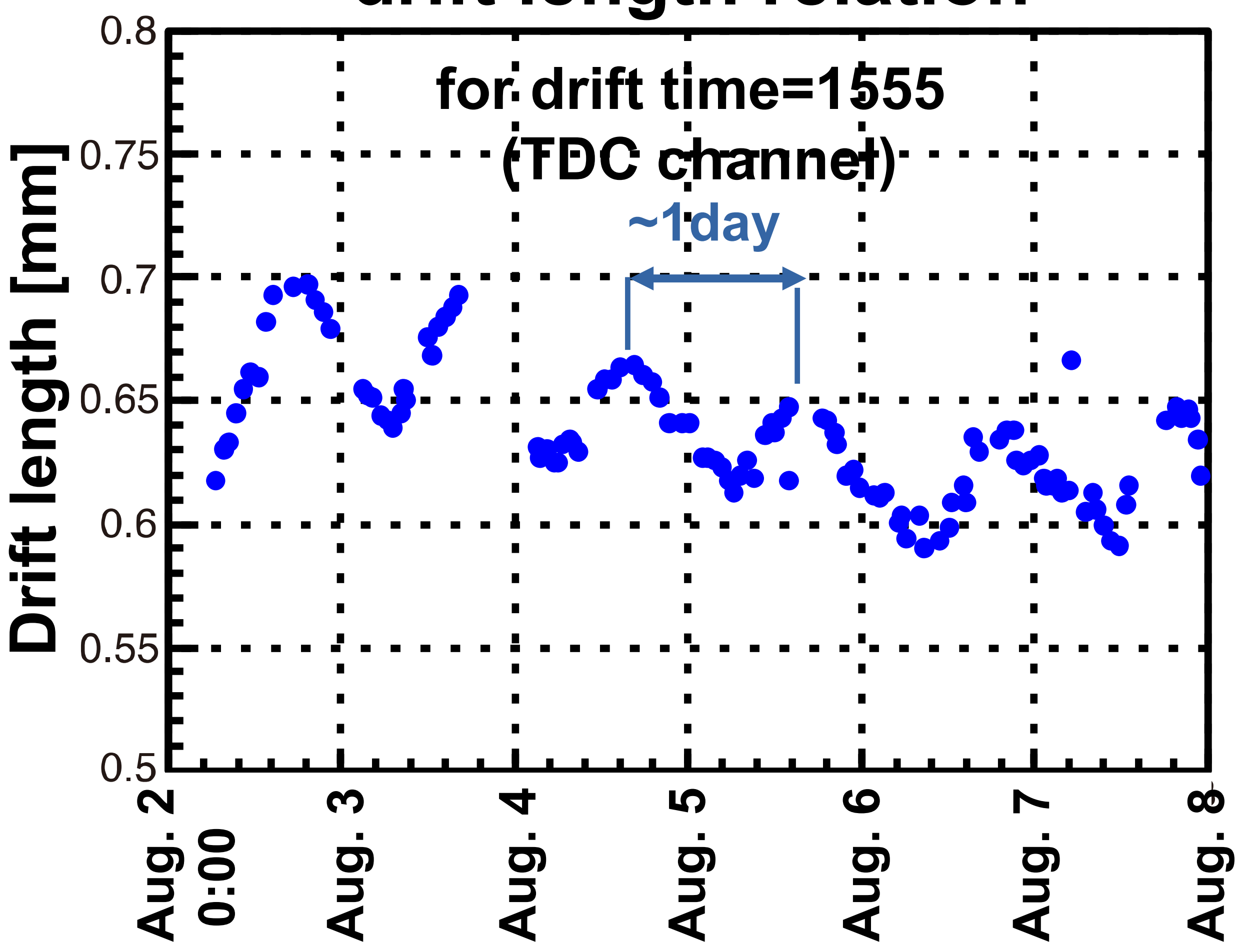
S437: MWDC Analysis

- MWDC (XX'XX'UU'VV') ×2 were used
- Tracking :
  Drift time (measured) → Drift length → χ^2 fitting for 2 MWDC
- Iterative analysis for calibration :
  Temporary drift length → tracking → evaluate and update drift length
- Time dependence of drift time to drift length relation

Drift length calibration



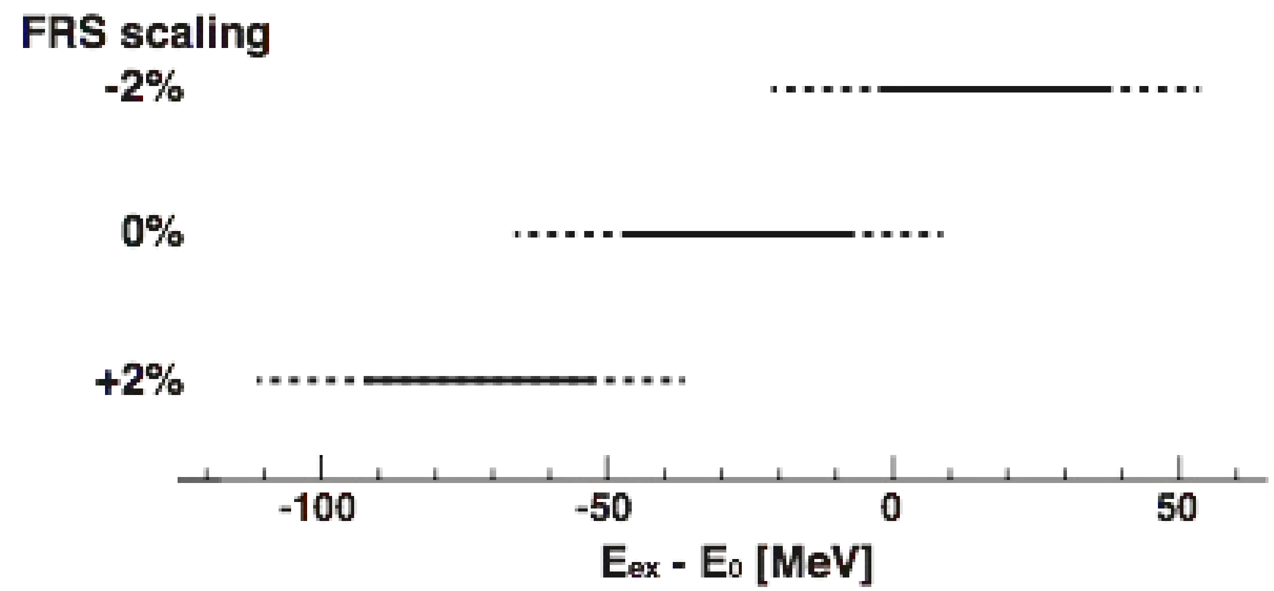
Time dependence of drift time to drift length relation



S437: production and reference runs

<u>production run:</u>

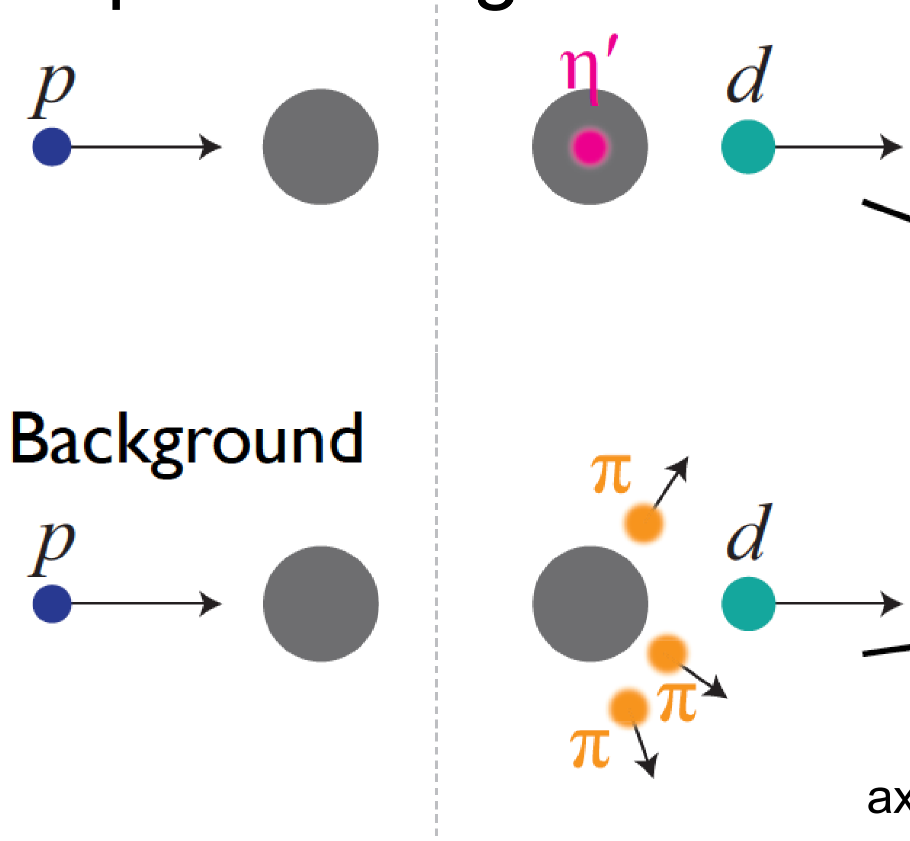
$^{12}C(p,d)$ @ 2.5 GeV
with Bρ settings from -2% to +2%
Relative to η’ production threshold
covering $-100 \lesssim E_x - E_0 \lesssim 50$ MeV

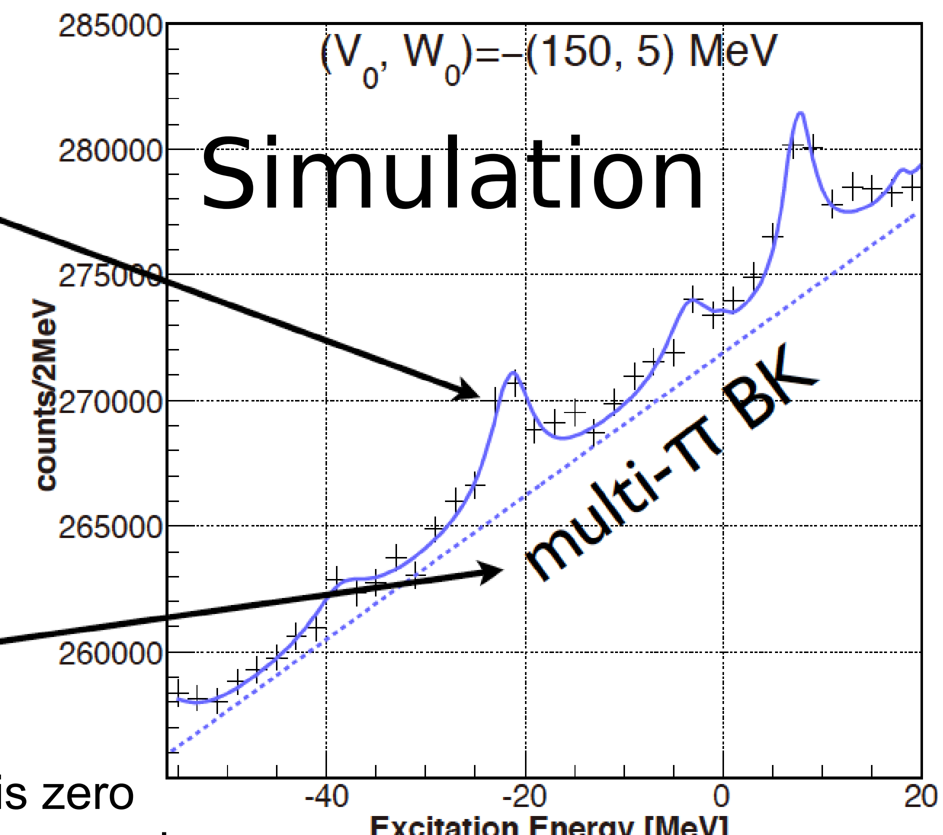


bound state region

<u>reference run:</u>

D(p,d) @ 2.5 GeV for
determination of multi-pion background





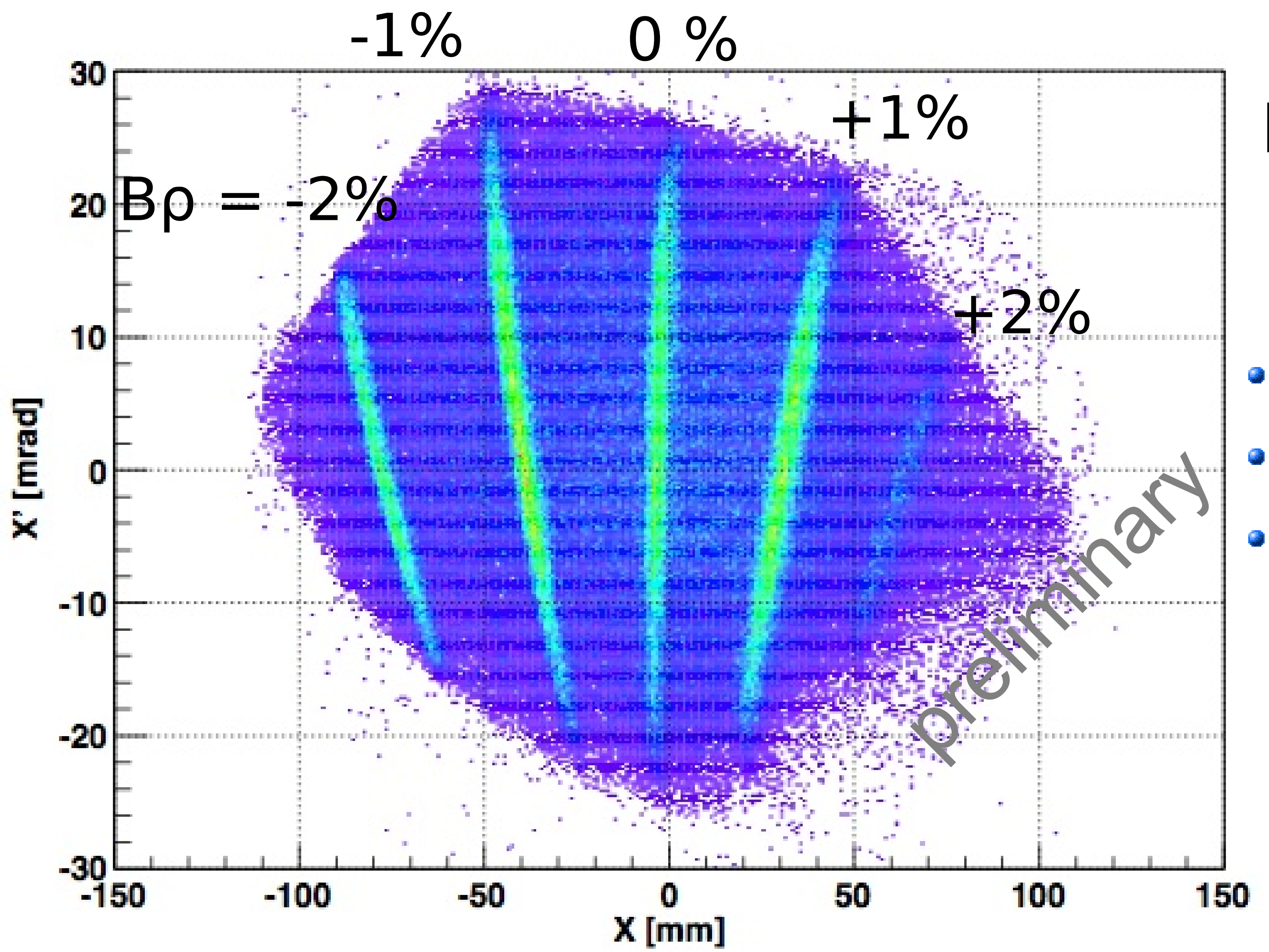
axis zero suppressed

S437: Calibration reaction

for each Bρ setting:

calibration run: D(p,d)p @ 1.6 GeV

elastic p-d scattering produces deuterons of 2.8 GeV/c at 0^0



MWDC at S4

information on

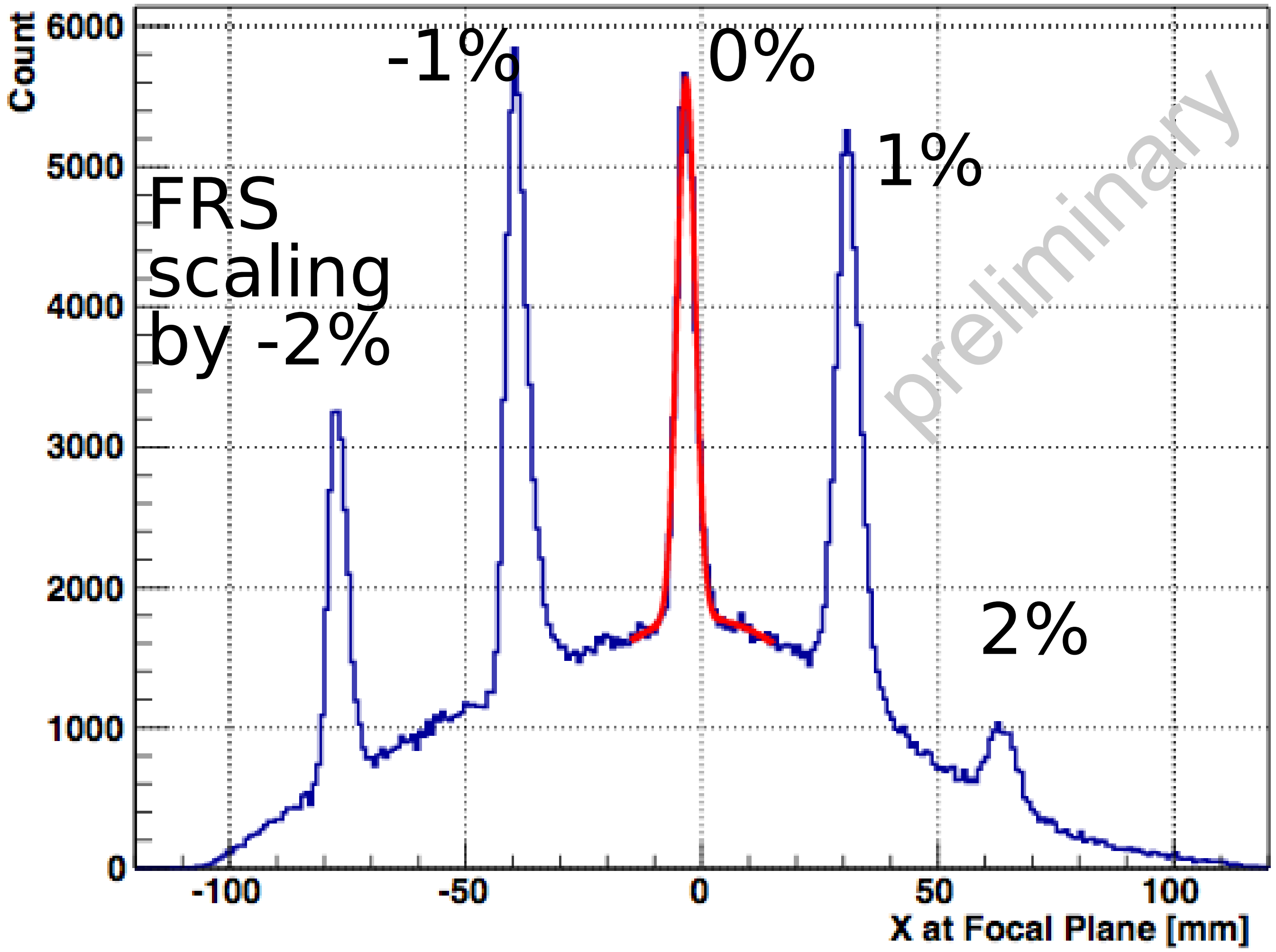
- beam optics
- missing mass resolution
- stability of the system (focus, dispersion, higher-order aberration)

X (horizontal position) - X′(angle) by MWDC

→ (x|a), (x|δ), (x|aδ), (x|aa), ...

S437: Calibration reaction

Focal plane position (online, ion-optics roughly corrected)



σ_X = 2.7 mm (CD_2 calibration run)

- energy loss and straggling calculation
- spectrometer momentum resolution
- beam momentum spread

$\sigma_{\text{missing mass}}$ ~ 2 MeV/c^2 (production run with ^{12}C 4 g/cm^2)

Experiment S437

production run (≈ 5 days): C(p,d) @ T_p = 2.5 GeV

intensity (3-4) 10^{10} p/spill

C- target: 4 g/cm^2; σ_{mm} ≈ 2 MeV/c^2

Missing mass spectroscopy

Bρ settings of the FRS from -2% to +2%
to cover excitation energy range of possible η' mesic states
from -90 to +40 MeV

<u>for each Bρ setting:</u>

- calibration runs D(p,d)p @ T_p = 1.6 GeV
- reference runs D(p,d) @ T_p = 2.5 GeV

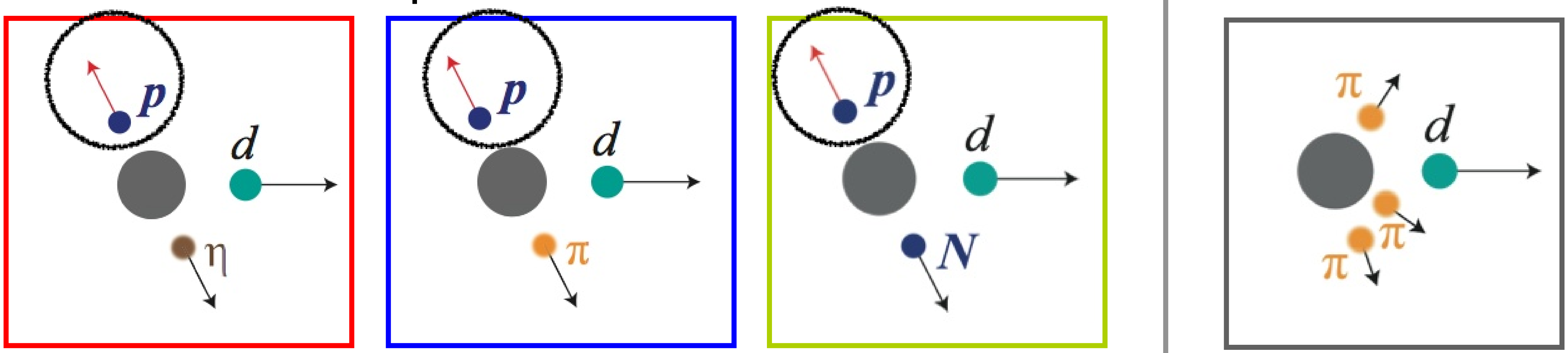
  to determine multi-pion background

Analysis ongoing

Tagging decay proton @ Super-FRS

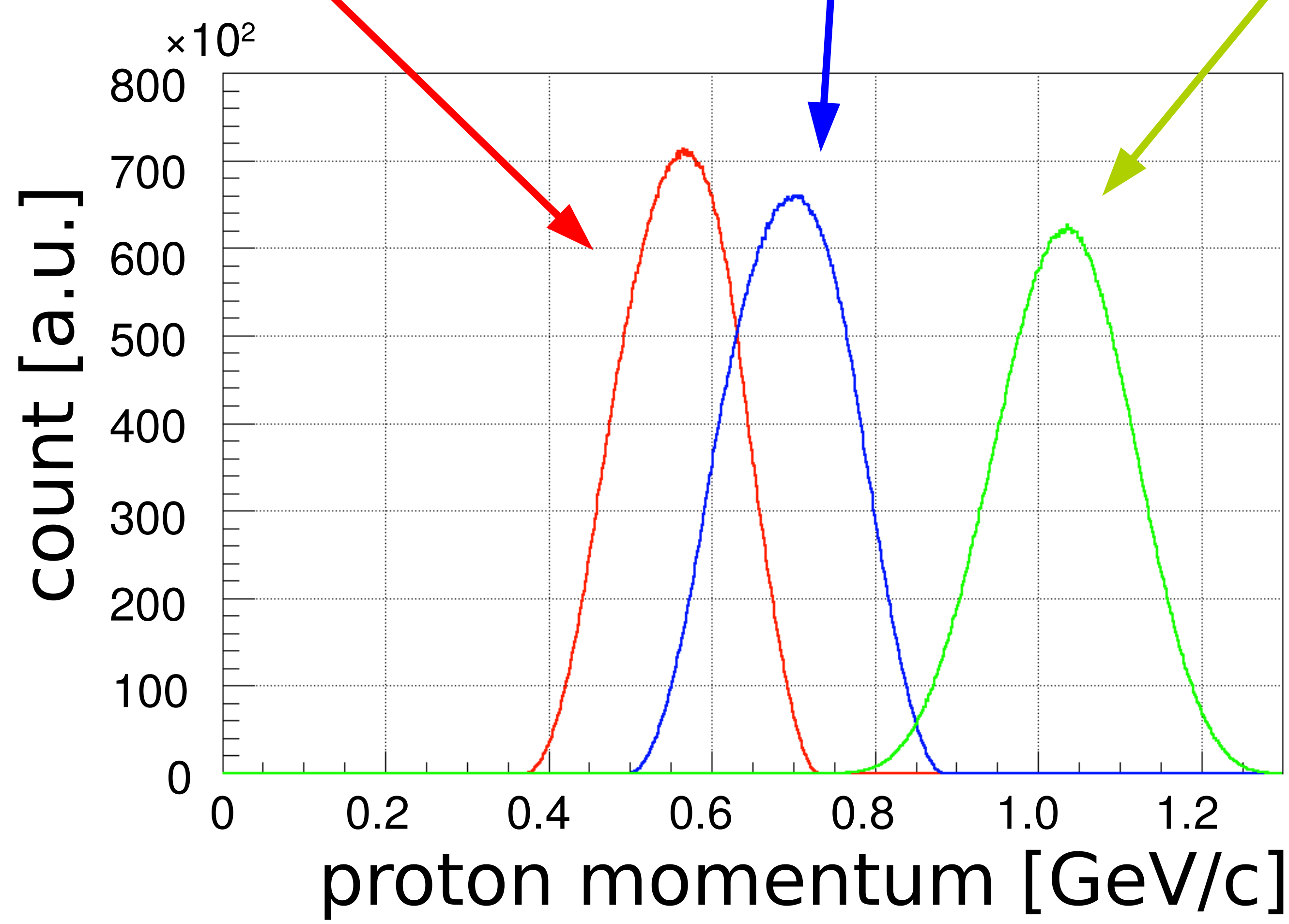
signal
η′ mesic nuclei

background
multi-π production

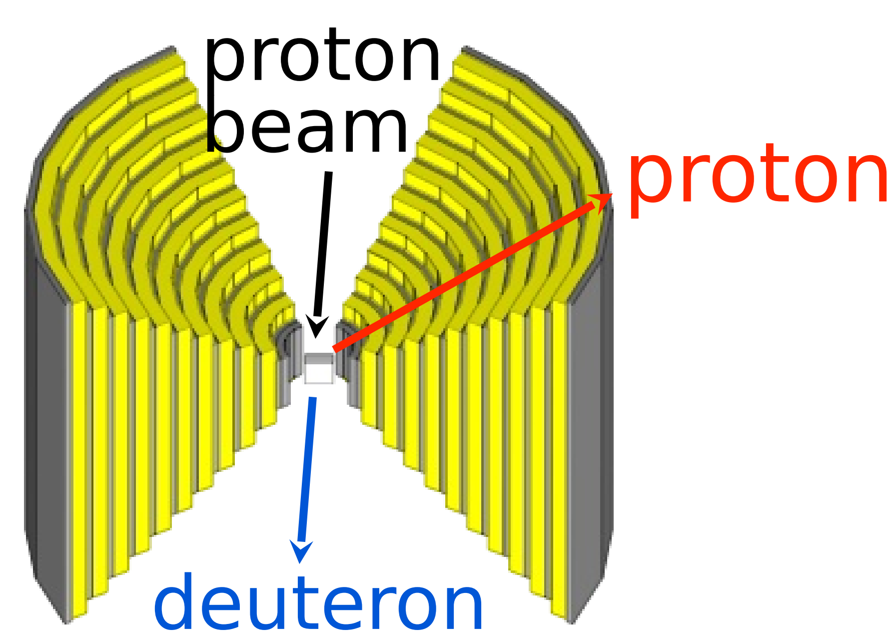


1 nucleon absorption

2 nucleon absorption

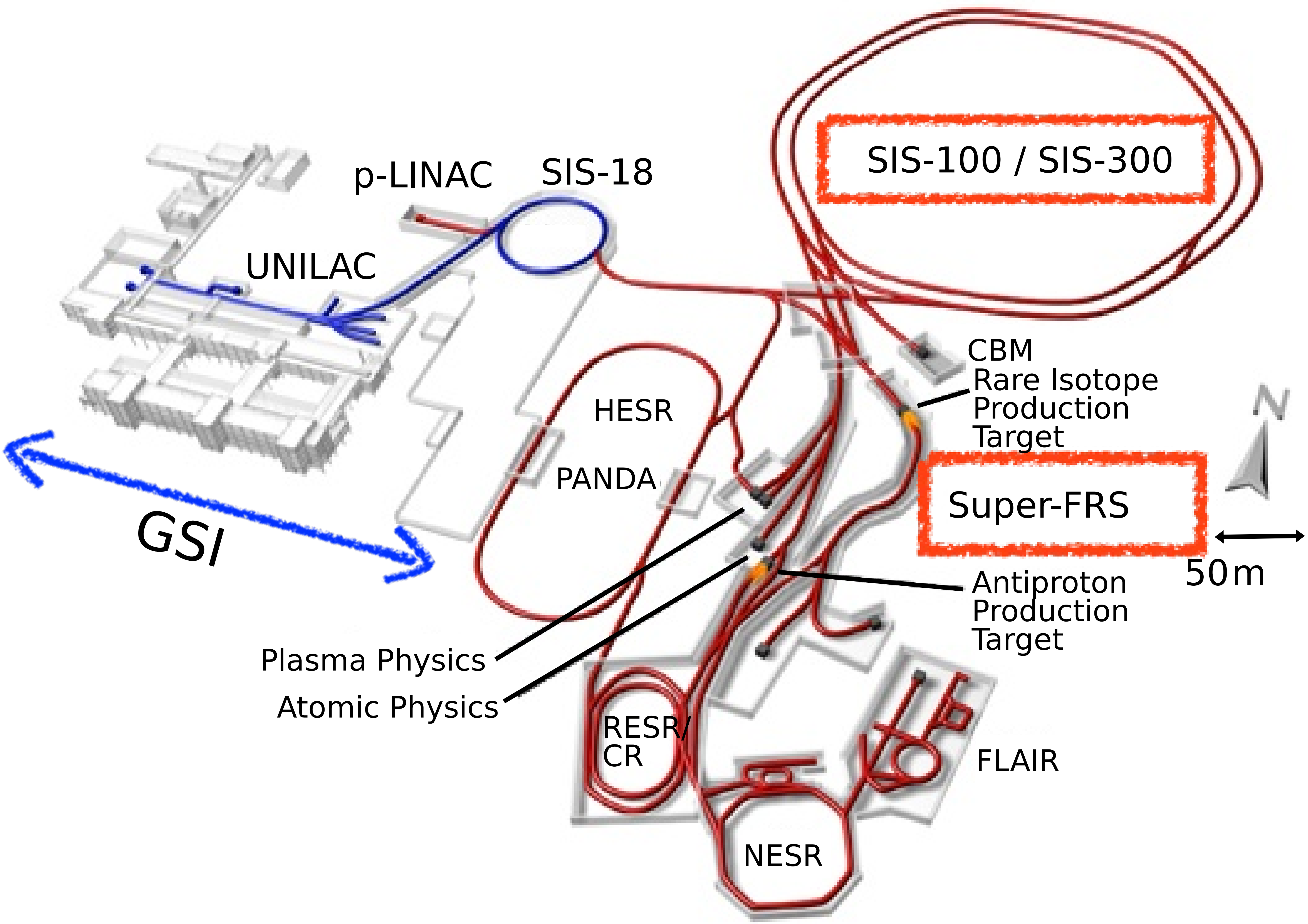


sampling calorimeter
(conceptual design)



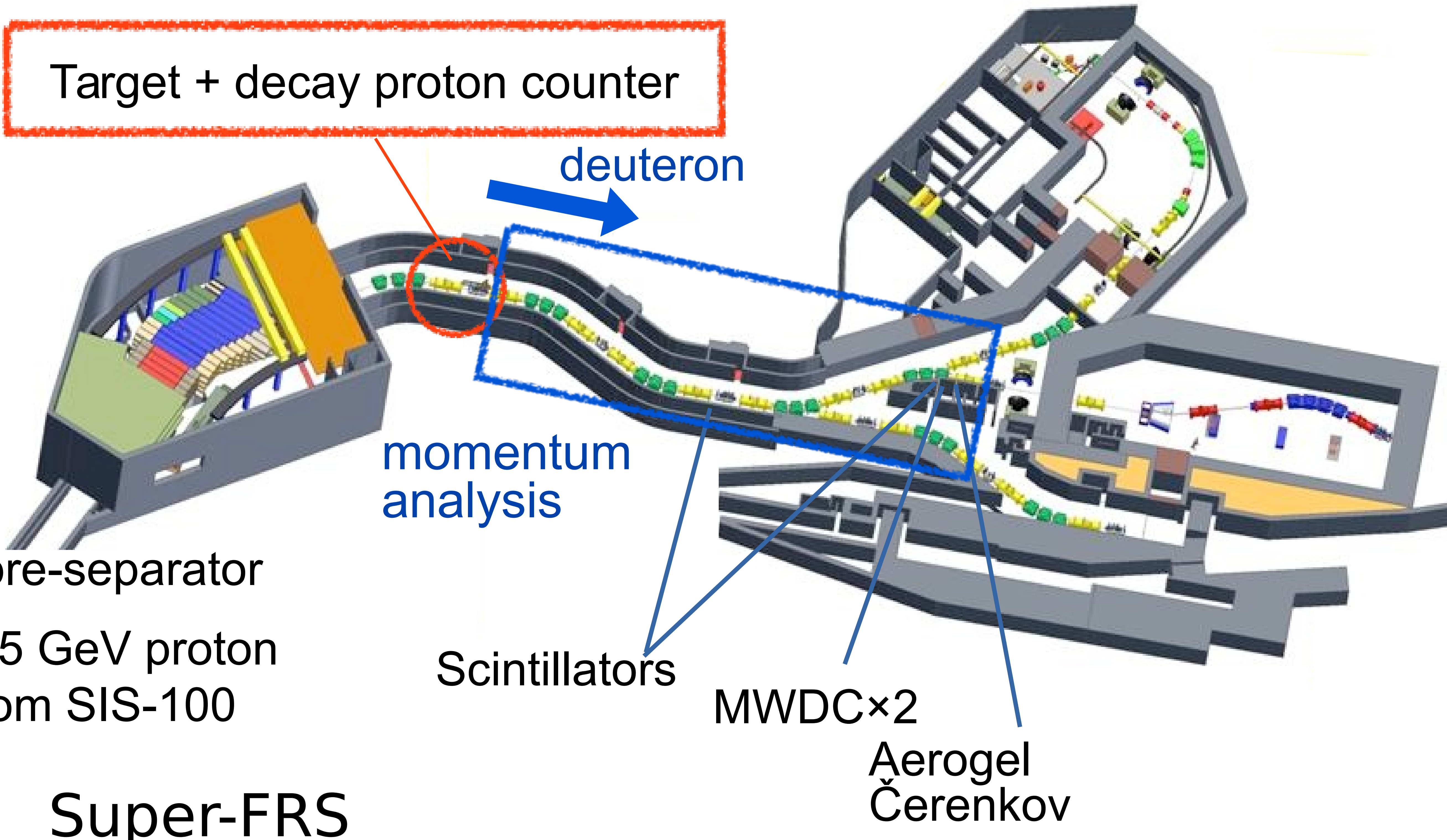
Future Plan at FAIR

Facility for Antiproton and Ion Research (FAIR)



Experimental setup at Super-FRS

Setup plan for semi-exclusive measurement



Summary

1. Scattering length |a| determined in η'N reactions

2. Optical potential determined in η'A reactions

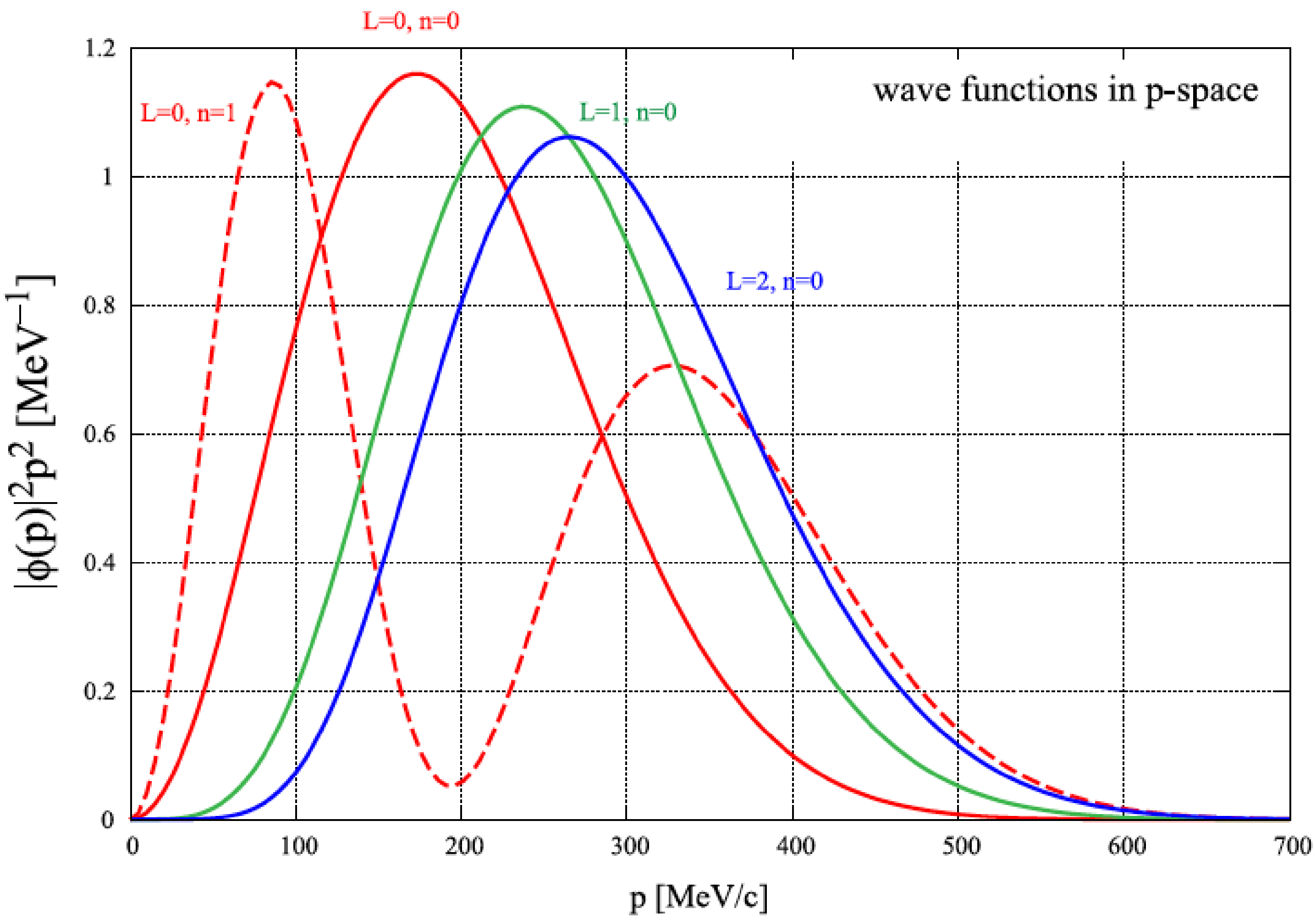
3. S437: Missing mass spectroscopy of population of η'-mesic states

4. Outlook: Missing mass spectroscopy and decay of η'-mesic states

Backup

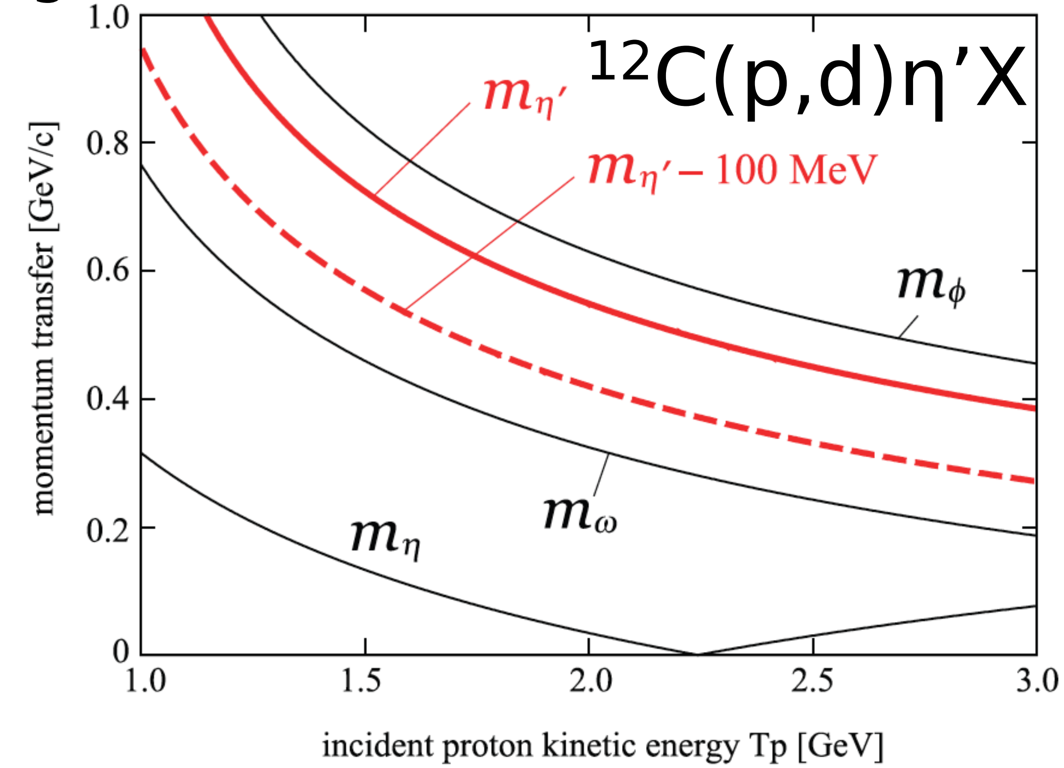
Momentum transfer ^{12}C(p,d) reaction

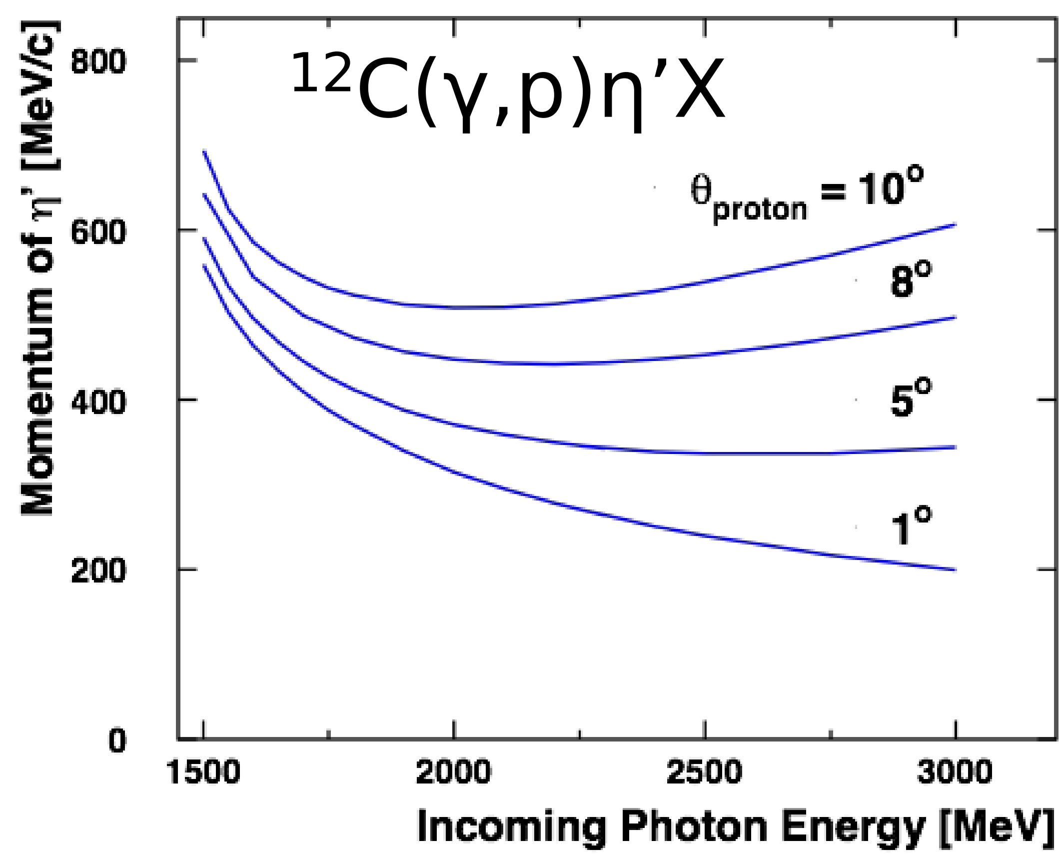
wave functions of η' bound states
in momentum space
H. Nagahiro, priv. com.



population of large $l_{\eta'}$ states
near production threshold

momentum transfer
H. Nagahiro et al.,PRC 87 (2013) 045201





The real part of the ω-nucleus potential

J. Weil, U. Mosel and V. Metag, PLB 723 (2013) 120

$\omega \rightarrow \pi^0\gamma$

sensitive to nuclear density at production point

- measurement of the excitation function of the meson

in case of dropping mass -
higher meson yield for given $\sqrt{s}$
because of increased phase space
due to lowering of the production threshold

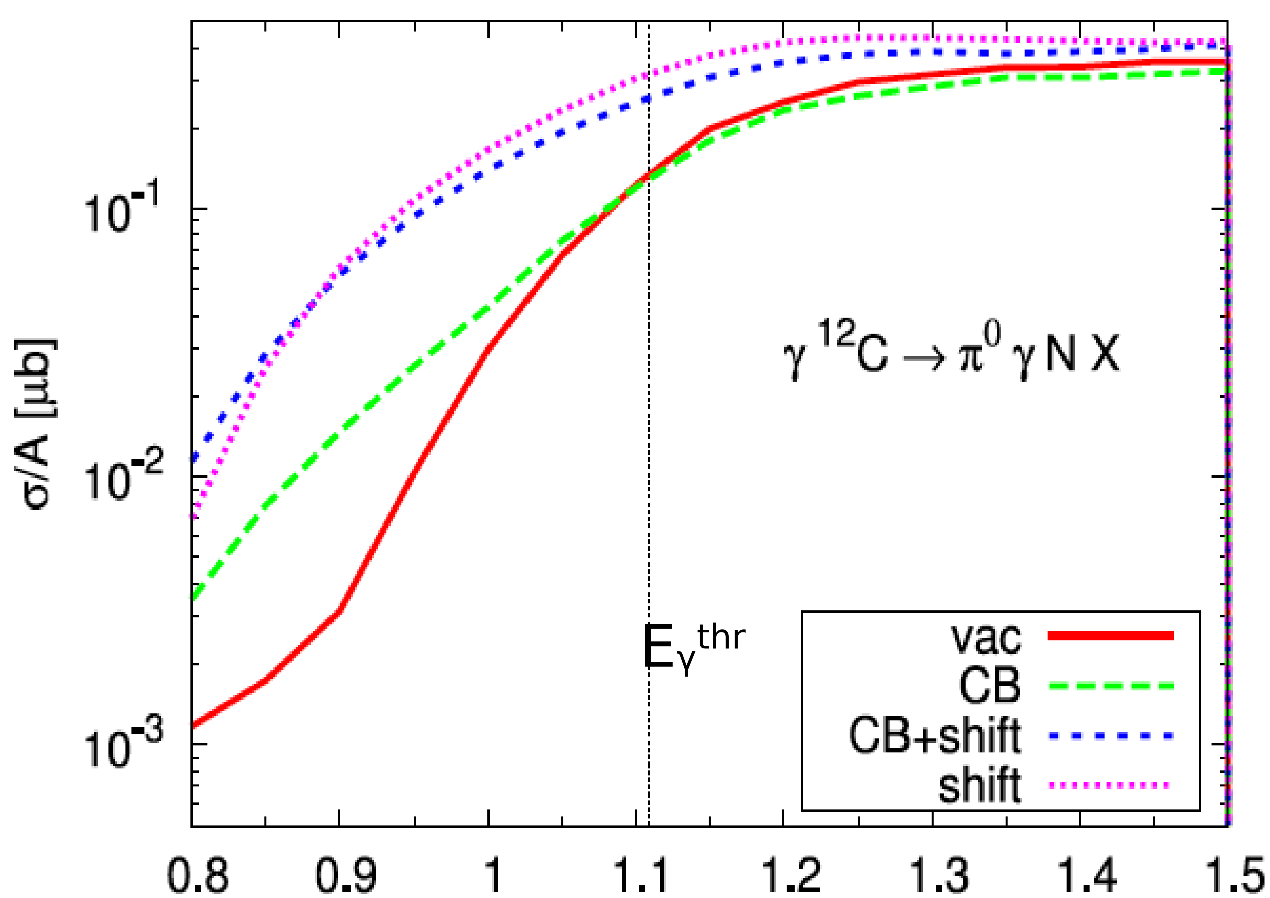
⇨ cross section enhancement

- momentum distribution of the meson:

in case of dropping mass - when leaving the nucleus hadron has to become on-shell;
mass generated at the expense of kinetic energy

⇨ downward shift of momentum distribution

$\pi^0\gamma$ excitation function



$\pi^0\gamma$ momentum distribution